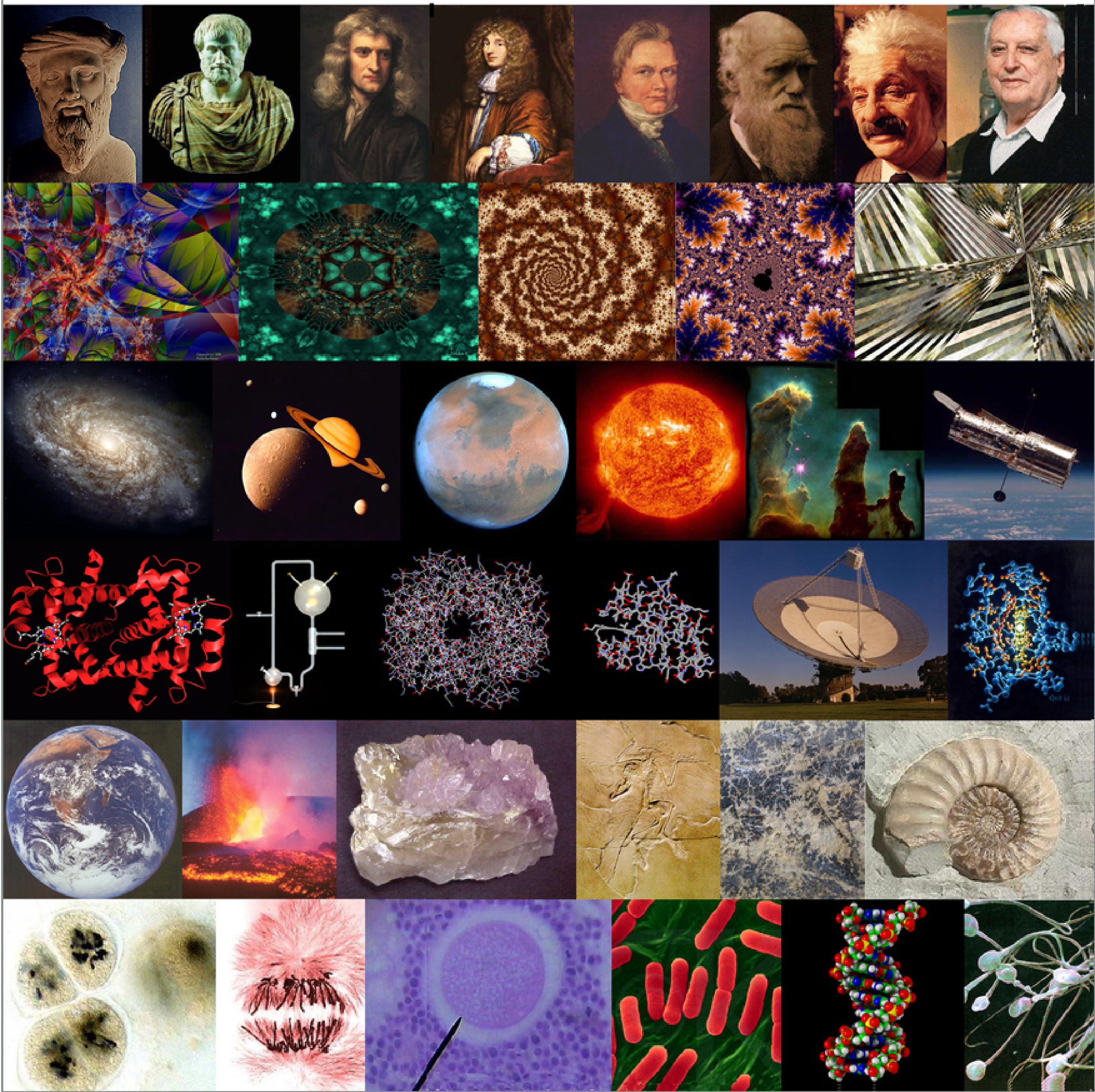
Hernâni L.S. Maia, Keith G. Orrell and Ilda V.R. Dias

Origin of Life

Recent Contributions to a Scientific Model



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Graphic design and pagination: Hernani L.S. Maia

Index

Nothing is more dangerous than a dogmatic worldview — nothing more constraining, more blinding to innovation, more destructive of openness to novelty.

Stephen Jay Gould (1941–2002)

Preface

THE ORIGIN OF LIFE. THIS MOST fundamental issue has for centuries puzzled and motivated philosophers, thinkers and scientists, especially challenging the understanding of all thinking people, particularly motivating philosophers and scientists, and especially biologists and chemists. Approaches to this problem have varied from the most speculative to the most rational and scientific. Our increasing knowledge of the physical world, achieved particularly during the past two centuries, has made it possible to identify clearly key elements in the problem and this has led to the systematization of processes that are crucial to an investigation of this matter.

But in parallel with the progress made by professional researchers the subject has remained a key issue for everyone with any curiosity about the intrinsic nature of Life and how it originally appeared in our universe.

Being a multi-disciplinary subject it has occupied a very fertile ground for its development particularly from the stage when scientific discoveries began to assert themselves beyond conventional disciplinary boundaries, and from where their wider implications could be seen. The subject also gained a new impetus when biochemistry began to establish itself as a key area, extending knowledge across the more traditional and limiting approaches of biology and chemistry.

However, in recent decades two most decisive issues pertaining to the origin of Life have become apparent. These are the discoveries, firstly, that *Life not only subsists but thrives under extreme physical conditions*, and, secondly, that *the chemical elements associated with terrestrial life are also common in interstellar space where they exist in varying abundance; moreover, organic molecules, many of which are crucial to Life as we know it, also exist in the giant molecular clouds where stars form in our galaxy and in external galaxies*.

If, at first sight, these two discoveries might seem disconnected, the subject of the origin of Life integrates them in a most exciting way — it is no longer just a search for "how Life started" but extends to "how, when and where it started", and even to more ambitious questions such as "is the Life we know the only possible type?".

Recent decades have provided amazing advances in virtually all areas of knowledge, particularly scientific knowledge. Such advances have caused many disparate areas of knowledge to move closer together, thereby enriching and widening current understanding.

A specific example of seemingly unconnected discoveries associated with the subject of this book is the exploration of the seabed at depths never before reached and only made possible by recent technological developments where living species have been revealed to thrive in conditions of excessive darkness, temperature, atmospheric pressure, acidity, and other environments considered until recently quite adverse to Life.

Another such example is the development of astronomical observations, using ground- and space-based telescopes, working in newly accessible regions of electromagnetic radiation, such as infrared and millimeter wave bands. These instruments have identified an increasing number of molecular organic compounds in the interstellar medium, particularly in the cold, dark molecular clouds. This has enabled our understanding of the processes involved in the formation of these molecules to be greatly extended both through appropriate physical models and, in some cases, through laboratory experimentation. In some cases even simulation and replication of some of the intimate processes that occur at the surfaces of dust grains in the interstellar medium has been possible.

Simultaneously, observations with telescopes of increasing light-gathering power, sensitivity and resolution, have led to considerable advances in the observation and characterization of star formation, inside dense and opaque "cocoons" in these clouds. The study of the earlier stages of stellar evolution when the stars begin to emerge from those cocoons is also becoming observable in the infrared and millimeter wavebands. These observations are crucial to our knowledge of the phenomena occurring at such early stages when the intense ultraviolet radiation greatly influences the immediate circumstellar environments and the molecular clouds themselves.

"Origin of Life — Recent contributions to a scientific model" deals and interconnects all these issues. The first part "Life: its origin and diversity on Earth" addresses and discusses the main theories that emerged over the centuries of civilization on Earth, and ends with the remarkable recent discoveries of Life in extreme physical conditions.

The second part "The current search of the origin of Life" focuses on the basic constituents, processes and scientific advances in our search for a chemical basis for Life.

The third part "The search for Life beyond Earth" focuses on space exploration of the Solar System, describing the space missions most relevant to this topic. This part of the book also includes a comprehensive description of the characteristics of the planets and satellites within our Solar System that are potentially the most viable places where Life existed in the past, where it may currently exist or where it may possibly exist in the future.

The search for Life in outer space is no longer thought to be a question of receiving communication from intelligent civilizations, but of locating regions in space where conditions and characteristics are potentially favorable to the emergence and evolution of Life. This research involves issues that constitute the cores of the new scientific disciplines of astrobiology and astrochemistry.

A specific example of current research in astronomy that relates directly to the search for Life is the hunt for exoplanets (planets that orbit other stars). If it becomes possible to identify non-gaseous exoplanets, similar to Earth, spectroscopic techniques may be able to identify, in their atmospheres, the chemical constituents compatible with the development of Life. However, among the more than three hundred exoplanets identified so far, the vast majority are gaseous giant planets, similar to Jupiter, and therefore not propitious to terrestrial life as we know it.

The recent successful launch of the Herschel Space Observatory provides exciting potential to advance our knowledge of the Universe. This observatory includes a telescope with a 3.5 diameter mirror that operates in a wide wavelength range from far IR to submillimeter, and should provide unprecedented insight into the existence of molecules in space associated with the origin of Life.

A major opportunity for further insight into the origin of Life is likely to arise in the near future, with the project ALMA (Atacama Large Millimeter Array), the first astronomy project conceived on a truly global scale. It is already under construction on the Chajnantor plateau (at approximately 5100 m) in the Atacama desert, in Chile, and should be completed in 2013. It is a partnership between the ESO, the European intergovernmental organization for Astronomy, the National Science Foundation in the United States, the National Research Council of Canada and, jointly, the National Institutes of Natural Sciences of Japan and the Chinese Academy of Taiwan. It consists of 62 antennas, each of 12 meters in diameter, designed to work in millimeter and submillimeter bands in interferometric mode. The ALMA project will investigate the origin of the first large structures formed in the primitive Universe, which are now observable at submillimeter wavelengths as a result of the expansion of the Universe. It will also research the origin of stars, by allowing us to 'see' much deeper inside the dense molecular clouds and register the submillimeter radiation emitted in the very early stages of formation of new stars.

We know that molecules dominate at the temperatures and densities prevailing in the interstellar clouds. Amongst them are the molecules that are the building blocks for Life. However, right now we can but speculate on the contributions of these two observatories for furthering our insight into the origin of Life.

This book aims to produce an up-to-date overview of current thinking on the origin of Life, and on how this knowledge has evolved over the centuries in chemistry and related areas. It also reviews recent developments in space exploration of the Solar System related to the search for Life. Its subject matter should be of interest to all of a curious disposition, scientists and non-scientists alike, who wish to learn more on how, when and where Life began in our universe.

Teresa Lago, Oporto 15 April 2010

Introduction

THE GREEK CIVILIZATIONS POSSESSED SUPREME wisdom in not subordinating to the authority and knowledge of their Gods the capacity of man to understand the world. Given their lack of a scientific technology and other appropriate means, it was only by way of thought and reflection that their philosophers were able to anticipate how European civilization would develop over the centuries, from its earliest conceptions and discoveries to successive revolutions of thought, from the start of the Renaissance to the culmination in our present culture. Many of these ideas were inherited by the Arabs but not accepted by the Roman Church until St. Thomas Aquinas attempted to reconcile the writings of Aristotle as expressions of the divine glory. From then on, usually under the domination of the Church, universities' teaching of Greek Culture was seen as a sign of modernity. It was then possible to learn that, as early as half a millennium before our present era, Xenophanes and Anaxagoras had speculated upon the possibility of Life existing in celestial places. Since immemorial times Man may have meditated on the meaning of the apparent shape of a human face that could be observed on our sister satellite during full moon nights. But in Rome not everything coming from the Greeks was accepted, and anyone daring to follow another way would surely have met Giordano Bruno's destiny, death by fire. By that time, the politically correct model for the world was the geocentric model of Ptolemy, dating back to the start of our present era. Nicolas Copernicus dared to propose a heliocentric model, but died before his ideas were published. Galileo Galilei, a follower of Copernicus, might have met the same destiny as Bruno had he not surrendered his thoughts, at least partially. But it was the cumulative effect of scientists and astronomers working until the middle of nineteenth century, notably Galileo Galilei, Johannes Kepler, Christiaan Huygens, Isaac Newton, and Friedrich Bessel amongst others, that necessitated removal of our Earth from the center of the known universe.

In the sixteenth to eighteenth centuries the light emitted by our Sun allowed telescopic observation of the planets to be made, and the intrinsic nature of light was pioneered by the Englishmen Thomas Harriot and Isaac Newton, the Dutch astronomer Christiaan Huygens and the French physicist Augustin Fresnel. They concluded that light possessed both corpuscular and wavelike natures depending on the nature of its investigation. It was left to James Clerk Maxwell and Heinrich Hertz in the following century to explain that light and radio waves are two different manifestations of the same radiation that constitutes the electromagnetic spectrum. At that time, bitter discussions were still taking place

with regard to the age of the World, i.e. was its age the modest one (about 6000 years old) calculated a few centuries ago by the cleric James Ussher, or the very much larger figure (billions of years old) proposed by geologists? In fact, patient and exhaustive work on collecting plant and animal fossils carried out systematically by numerous paleontologists such as Georges Cuvier, William Smith, Alcide d'Orbigny, Pictet de la Rive, Albert Oppel, John Joly, Othenio Abel, A.M. MacGregor and, later, Theilhard de Chardin led to a realization that the Earth was exceedingly old and that the past had been populated by different species many of which had now become extinct.

Whilst understanding the nature of light phenomena was a great challenge to scientists, as mentioned above, understanding the intrinsic nature of matter of which everything is composed was an even greater challenge. This led alchemists as far back as the Persian Empire in 700–550 BC to search for metal transmutation and for the elixir of long life. But two important questions have always prevailed, one concerning the basic structure of matter, and the other concerning how to fashion and utilize matter to the benefit of civilization. Although the Greek philosophers considered matter to be made out of atoms, practically nothing was known for certain about its nature and structure, Only in the seventeenth century, with the work of Henry Cavendish, Antoine Lavoisier, Joseph Proust, Jeremias Richter, John Dalton and Amadeo Avogadro, has a sufficiently complete body of doctrine been established to confirm the atomic nature of matter. Furthermore, until the middle of the nineteenth century there was a widespread belief that inanimate matter and living matter were different realities. The latter was thought to be enlivened by a 'vital force' and was therefore beyond the synthesis of Man. Anyone challenging this principle would be accused of witchcraft and treated accordingly with fire. This superstition was overcome when, by chance, the chemist Friedrich Wöhler synthesized urea in his laboratory from inorganic materials in 1828. This was only 10 years after the novelist Mary Shelley had famously created her Frankenstein monster, a violator of the divine laws, a manufacturer and a manipulator of human beings! Shortly after Wöhler, the German chemist Adolph Strecker synthesized an amino acid — amino acids are constituents of proteins — and another chemist, the Russian Aleksandr Butlerov, converted formaldehyde, which he had discovered, into sugars. However, the debate between the realities of inanimate and living matter continued. Some researchers, notably Wilhelm Wundt, Alfred Fouillée, C. Lloyd Morgan, Leonard Hobhouse and Philip Masci, persons often of a religious inclination, contended that a "vital force" (the vitalist or dualist principle) was essential to differentiate between the two categories of matter, whereas others considered there to be no fundamental difference except for its degree of molecular complexity. This view was argued by Thomas Huxley, Ernst Haeckel, Edward Cope and others.

The nature of living matter became the great scientific and philosophical challenge in the second quarter of the nineteenth century. Matthias Schleiden and Theodor Schwann had found that living things are composed of cells, each cell containing a nucleus, first identified by the botanist Robert Brown. Thirty or so years later, shortly after Gregor Mendel had first described the laws of heredity, Friedrich Miescher extracted from cell nuclei a material he

called nuclein, later named nucleic acid, or, in modern abbreviated form, DNA. At the end of the century the chromosomal structure of the nucleus was established and shortly afterwards the results of Mendel were discovered. Until then these had been kept in the obscurity of the monastery of Brno, in the Austro-Hungarian Empire. It was from that point in time that the concept of evolution gained strength. The concept that the world constantly changes had been introduced a few centuries earlier by European thinkers and shared by the scholar Erasmus of Rotterdam, and the French naturalists Georges de Buffon and Jean-Baptiste Lamarck. But it was Charles Darwin who first gave expression to a detailed theory of evolution, based initially on the hypothesis of spontaneous generation (contradicted by Louis Pasteur) and, later based on a presumably chemical origin. However, evolutionary ideas continued to be challenged and there was endless controversy between monists and dualists, the latter, being invariably on the side of the 'establishment', advocating not only the "vital force" but also Bishop Ussher's calculation of the age of the World.

At the onset of the twentieth century it was remarkable to learn from the contributions of Max Planck, H.A. Wilson, Robert Millikan and Albert Einstein that all light is both corpuscular and wave-like, and that matter may even be converted into light energy, as happens within radioactive materials. Intense discussions continued to be fought over the age of the World, with William Thomson (Lord Kelvin) being one of the main protagonists for a biblical based age, confronting the geologists and Darwin's supporters for a far greater age. However, the phenomenon of radioactive decay of matter, as discovered by Ernest Rutherford soon became established as an accurate method of dating, and Arthur Holmes and Friedrich Paneth applied the technique to date rocks and meteorites. This provided overwhelming evidence that our planet has existed for several billion years and that the Universe is even older. Although the value and significance of these philosophical and cosmological measurements may not have been immediately obvious, it provided confirmation that the Earth has not always existed, that it had an origin, and that the Universe itself is of finite age. Maxwell's work on the electromagnetic nature of light played a key role in the further understanding of the nature of energy and matter. Scientists such as Wilson, Millikan, Rutherford, Bohr, Marie Curie, Planck, Einstein, Heisenberg, Schrödinger and Gamov all made invaluable contributions to deepen this understanding. It led to a much greater appreciation as to how and why matter and energy interact, and of how to control and use these interactions. For example, the discovery of the photoelectric effect, for which Einstein received the Nobel Prize for Physics in 1921, is now used in many applications such as infra-red remote controls. Analysis of the interactions between energy and matter has made it possible to characterize chemical compounds from the properties of the light they emit, absorb or reflect. This led to the powerful and diverse technique of spectroscopy being used both in analytical laboratories and in many optical and radio telescopes. The recent use of space telescopes has allowed astronomers to find and characterize chemical materials in places of the Universe at many billions of light years from us — and inevitably many billions of years in the past.

After Wöhler, Strecker and Butlerov, the progress of chemistry, especially of organic chemistry, was so rapid that in 1902, the so-called forces of evil of the vitalists were subjugated in favor of rational chemical experiments and earned the German, Emil Fischer, the second Nobel Prize in Chemistry. It was during subsequent years up until 1920, that the genetic structure of chromosomes was discovered, primarily by geneticists Walter Sutton, Thomas Morgan and Osvald T. Avery. The geneticists George Beadle and Edward Tatum then described the chemical action of genes in conjunction with proteins and, by the end of the Second World War, Avery had discovered that genes are made up of deoxyribonucleic acid (DNA). Meanwhile biological chemistry had become an established discipline to be followed soon after by the discipline of biochemistry. Notable exponents of these subjects were Albrecht Kossel, Aleksandr Oparin, Wendell Stanley, and Edward Tatum amongst others. The Russian biochemist Oparin, often called the Darwin of the 20th century, was one of the great pioneers in proposing a chemical origin for Life, this being later taken up by the British biologist John Burdon Sanderson Haldane. However, it was the work in the 1950s of the American physical chemist Harold Urey, his research student, Stanley Miller, and later by the Spanish biochemist, Joan Oró, that established a body of evidence supporting a chemical origin of Life on Earth and the basis for a theory of chemical evolution of Life. In the previous century the Irish physicist John Joly had suggested that Life could have arisen on Earth some ninety thousand years ago, but the work of Rutherford, Holmes and Paneth in dating geological materials, made it possible to date the oldest fossils known at that time, the trilobites, to about six hundred million years old. In the second half of the twentieth century even older microscopic fossils were found, and a little more than a decade ago, William J. Schopf found in Australia microfossils about three thousand five hundred million years old, as old as the oldest rocks on Earth! These findings raise many questions concerning their origins. Answers to these are now being sought by several research programs, many connected with space science.

During the nineteenth century several meteorites had been studied by chemists as well known as Berzelius, Wöhler and Berthelot, who found that they contained organic matter, but, for lack of analytical resources, was of unknown identity. However, it had already been known for some decades that these alien bodies transport to the Earth chemical compounds that could only have been generated elsewhere in the Universe, possibly even before the Solar System was formed. From where did they come? During the first quarter of the twentieth century Albert Einstein, Aleksandr Friedmann and George Lemaître predicted, and Edwin Hubble established, that the cosmos is constantly expanding. This gave rise to the theory of the origin of the Universe that involved an initial explosion, from which all matter was subsequently formed. This proposal was made by Lemaître, developed by Gamov, and described deridingly as the "Big-Bang" by Fred Hoyle, who disbelieved the idea and was of the opinion that the Universe had no beginning but existed in a steady state. Today, with the Hubble Space Telescope having searched many areas of deep space it is thought to be space that expands and not the galaxies. Owing to the long time taken by light to travel such

extensive distances, powerful telescopes are able to record events that have occurred many millions or billions of years ago shortly after the Big-Bang.

The beginning of the second half of the twentieth century was marked by the notable establishment of the chemical structure of DNA, which earned Francis Crick, James Watson and Maurice Wilkins the Nobel Prize in Physiology or Medicine in 1962. Knowledge of this structure has enabled, half a century later, genetic manipulation to become a routine activity using sophisticated computerized analysis of DNA sequences. The use of such equipment also allows the chemical synthesis of portions of natural or artificial DNA that can serve to produce new medical drugs. A genetic material simpler than DNA, called RNA, appears to be associated with the most basic mechanisms of Life and, therefore, is the subject of much current attention by biologists.

In the mid-1970s, Francis Crick and Leslie Orgel revived the concept of panspermia (or panspermy), originating from Greek civilization but developed more recently by the Swedish physical chemist Svante Arrhenius shortly after receiving the Nobel Prize for Chemistry in 1903. They suggested that Life on Earth has arisen through spores carried by spacecraft sent by intelligent beings or aliens (directed panspermia)! However, that idea had virtually no supporters! But in the early 1980's, new laboratory results and chemical analysis of meteorites led to a reappraisal of the erlier experiments of Urey and Miller, and of Oró and others. This led to the idea of 'chemical panspermia', which was further supported half a decade later by observations of comet "Halley". Indeed, during the last three decades it has become increasingly evident that the chemical elements generated from particles of matter emitted by stars produce very many compounds, amongst which are those indispensable to the production of the so-called monomers of Life— amino acids, nucleic bases, sugars and others. In the current state of science it is not possible to make conjectures about how, over some two or three billion years, such monomers progressed to the complex compounds that we know today in living beings. Some ten years after the appearance of Halley's comet, a meteorite recognized as having come from Mars, contained signs of fossils of unicellular living creatures. Very recently, unexpected findings show that certain forms of Life (extremophiles) can proliferate in very hostile environments perhaps as extreme as those of meteorites, comets and other small sized celestial bodies. So, through the centuries, theories concerning the origin and evolution of living beings have gone through periods of high and low support. Arrhenius' theory of "biological panspermia", now almost a century old, seems to have gained much respectability, presenting itself now as a complement or alternative to the "chemical panspermia" theory of the origin of Life on Earth. But if Life was not generated on our planet but elsewhere, then one falls back to the original question: how did it emerge? A more definitive answer to this huge question will depend on future results of missions to Mars and other planets.

In short, the progress made since the end of World War II in the observation of the Solar System and deeper space has led to the assumption that Life will not be exclusive to our planet, but is ubiquitous throughout the Universe. Thus, one of the current programs

of exploration of the Universe by the space agencies consists of the search for planets outside the Solar System; to date more than one hundred and fifty of these exoplanets have been found, but none have possessed the physical conditions to harbor Life. If scientific findings have always given rise to imagination and creation of fantastic stories of interplanetary travels and of alien beings, the realities that science is slowly revealing have always challenged and sometimes exceeded our imagination, showing that we almost only reinvent what probably has always existed, and rediscover what has always been part of our intuition.

Today these issues are strongly influenced by the results of the missions aimed at exploring the Solar System and the rest of the Universe, carried out by the space agencies of the richer countries, which include the U.S., Russia, Japan, Canada, China and several European countries gathered around the European Space Agency (ESA). At the end of the text, a bibliographic list organized by chapters is presented. It includes references to texts that may be found in full on the Internet, often in "pdf" form. Web addresses of good quality pages from sources of high reliability are also included. In view of the rapid progress occurring in the topics covered in this book, these web pages are particularly recommended, as many of them undergo regular updating.

One verse

ONE VERSE. Nothing more than a twinkling verse
against the cosmic equilibrium and the expansion of the Universe
in the tail of the most wandering comet
in the heart of space and its reverse
a singing syllable
one verse.

BEYOND the black holes and the interstellar lines
a sound in the space
an echo through the air
a tone a line a trace.

A SOUND of a sound: alchemy
of sighs and signals
no more than another form of energy
spectral images
of an inverted sun
a luminous point in the fractals
one verse.

Manuel Alegre, "Senhora das Tempestades", Publicações D. Quixote, 1998

FIRST PART

Life: its origin and diversity on Earth

Introduction

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Fig. 1
Phylogenetic tree
according to Carl R. Woese
"The Origin of Life", Carolina Biology Readers No. 13 (1984), Burlington, North Carolina.

Living beings are objects endowed with a project.[1]

SINCE REMOTEST TIMES MAN HAS BEEN questioning his origins and that of the other living beings. This questioning contains within it at least two questions, namely, how and when has Life occurred on Earth?— which today is still the only place where we know with certainty it exists. Over time, many attempts have been made to obtain answers. It was not by chance that the sacred texts of different religions did not fail to mention the origin of the Cosmos. Before Man had the means to observe and conceptualize the world it was mostly to such texts that scholars resorted. Because of the lack of better resources these texts provided acceptable explanations of cosmic origins. Strange as it may seem, even today, in the twenty first century, there are those who recognize such sources as the only ones deserving their acceptance, but this attitude now only prevails in circles with little or no scientific culture.

Science has contributed to an increasingly rational and objective knowledge of the Universe as a whole. Yet formulations of an eminently scientific nature have become mixed with others of little credibility, without any rational basis, including completely fanciful notions and crazy stories filled with allegories, such ideas having

1 Jacques Monod (1910–1976) in his book "Chance and Necessity".

been handed down from generation to generation. They all shared a common purpose of building an acceptable answer to the persistent question of the origin of the World, of Life and of Humanity.

Below, we will give an account of some conjectures that for centuries occupied the collective imagination and that in some way are the roots of what in more recent years have come to consolidate the body of theory that is generally accepted within scientific circles. Strange as it may seem, it was only at the end of the nineteenth century — just over one hundred years ago — that Science has begun to be able to contribute convincingly to a very gradual unravelling of the mysteries of our origins. Before we move towards our main goal, it is necessary to address an underlying but essential issue, namely, how do we define Life. In other words, how do we define a "living being"?

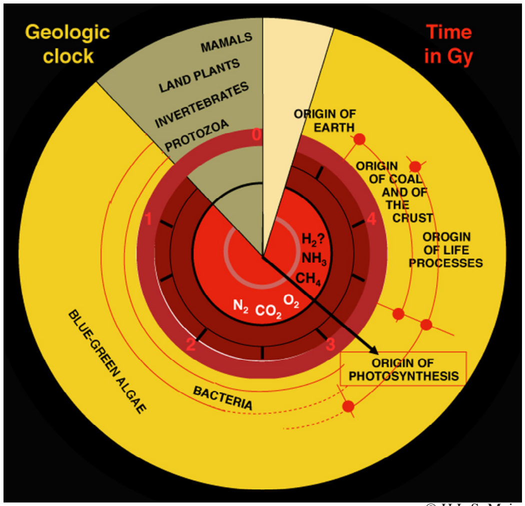
An answer to this question is far from easy. Indeed, despite centuries of Biology and millennia of Natural Philosophy a universal and precise definition of Life did not appear until recently. Many attempts at a definition have been shaped according to the specialty and singular perspective of their authors; some attempts have been incomplete and insufficient by leaving out irrefutable expressions of Life, other attempts have been too comprehensive ending up by including in the world of the living what is not alive. A reasonable definition, one that is general without being exceedingly inclusive, includes the following characteristics that are essential for an object to support Life: "it must be formed by a complex structure containing a large amount of heritable information, be able to replicate and evolve, have a complex structure endowed with homeostasis[2] and be characterized by a reproductive system and its own metabolism, in addition to the ability to fight continuously against the thermodynamic equilibrium, i.e. against death". Yet this definition still fails to please many authors for various reasons, including the fact of its being based only on the forms of Life that we know. As we shall see below, experience leads us today to seriously suspect that other forms of Life, of which we are currently unaware, may exist. This makes a single formulation of Life almost inevitably inadequate. It therefore, remains an open issue.

2 Capacity that living beings have to regulate their internal environment so as to maintain a stable condition.

Chapter 1

The age of Life on Earth

You cannot conceive anything so strange and unlikely that has not already been said by one philosopher or another.[1]



© H.L.S. Maia

Fig. 2
"Geologic Clock"
according to C. Ponnamperuma
"Cosmochemistry and the Origin of Life",
D. Reidel Publishing Company, Dordrecht, 1983

ASSUMING THAT WE ALREADY HAVE A sense of the essence of Life and before attempting to theorize on the subject, we will take a brief trip through time in search of answers about when it originated. The first attempt known in the West to establish the age of the Earth and of the world is due to James Ussher (1581–1656) who was born in Dublin, Ireland, and was Archbishop of Armagh, Primate of All Ireland and Dean of Jesus College, Oxford. Counting the number of generations after Adam and Eve in the Old Testament of the Bible, he concluded that the world was created on Sunday, the 23rd of October in 4004 BC, at 9:00 o'clock in the morning! Even at the start of the twentieth century this was the official date assumed by the Christian church for the Creation!

Later in the eighteenth century, the English astronomer Edmond Halley (1656–1743) suggested in the Royal Society of London that the age of the Earth could be mea-

1 René Descartes (1596–1650), "Discourse on the Method", 1637.

sured from the salinity of the seas, because, in his view, the salts of the oceans result from sediments carried by rivers and runoff. In the following century it was the turn of George Leclerc, Count of Buffon (1707–1778), in his book "Les Époques de la Nature", published in France in 1779, to propose an age for our planet based on the cooling rate of iron. His figure of 75,000 years was greatly more than the 6,000 years currently proclaimed by the Church. Then in the nineteenth century, applying Halley's approach, John Joly (1857–1933) calculated the sodium content in the oceans and estimated the age of the Earth to be 80–100 million years! Around the same time, based on the study of sedimentary strata and fossils, geologists, prominent among whom was the Scotsman Charles

Fig. 3
James Ussher (left), Edmond Halley (center) and George Leclerc (right).

Lyell (1797–1875), were inclined to conclude that the Earth was even older, and tended to the higher end of the range Joly had obtained. On this they were supported by Charles Darwin (1809–1882), who from his studies on the evolution of living beings became convinced that the planet would have to be even older, at least 200 million years old! But these figures were refuted by a person of great scientific prestige, William Thomson, better known as Lord Kelvin (1824–1907). He based his calculations on the cooling rate of the Sun and insisted that the age of the Solar System could not be greater than one-tenth of that proposed by Darwin. This controversy lasted for several decades, until a method was found, at the start of the twentieth century, to accurately date rocks. This method was based on measuring the rate of decay of radioactive material, and was originally proposed and implemented in England by Ernest Rutherford (1871–1937). The technique was convincingly applied by Bertram Borden Boltwood (1870–1927) in the U.S. and by Arthur Holmes (1890–1965) in England. In 1911 Holmes estimated the age of a

Fig. 4
Stromatolite.
Credit: NASA.
URL: http://rst.gsfc.nasa.gov/Sect19/Sect19_2a.html

Devonian rock[2] to be 375 million years! Since then, the dating of soils and other materials has become well established, and today the age assigned to our planet is estimated as being within the range 4.51–4.55 billion years (or 4.5 Gyr[3]).

If the method of radioisotope dating has proved to be of greatest value for determining the age of rocks, of equal importance has been the dating of fossils for evaluating the age of Life on Earth. The oldest fossils discovered so far date from about 3.5 Gyr and were found in Australia and South Africa. They are stromatolites[4] (Fig. 4), revealing the existence of dense masses of prokaryotic cells[5] and mineral deposits, and would seem to result from a community of diverse and complex photoautotrophic[6] organisms, probably of the type cyanobacteria.[7] Such structures are also found in tropical seas. In Australia, in the Apex Chert,[8] microfossils of the Archaean period have been discovered with an estimated age of 3.465 Gyr (Fig. 5). These are believed to be from organisms similar to filamentous cyanobacteria. However, this is not the oldest evidence of Life. Isotopes of carbon were detected in the graphite of Isua sediments (Greenland), which are the oldest known sedimentary record, and suggests possible carbon fixation and photosynthesis in rocks 3.8 Gyr ago. These microfossils of prokaryotic photoautotrophic nature, as well as the mineral records of Isua, reveal an evolutionary state that is already very advanced, suggesting that this state was preceded by much simpler living beings.

2 The Devonian period belongs to the Paleozoic era and is placed between the Silurian and Carboniferous, i.e. between 416 million and 359.2 million years.

3 Gyr = giga year; 1 Gyr = 1 000 000 000 years.

4 Laminated limestone fossil structure produced by colonies of bacteria with a round or columnar form with alternating layers of sediment.

5 Prokaryote is any cellular organism without nuclear membrane or organelles in the cytoplasm, except ribosomes, and with its genetic material in the form of continuous beams or helical ties.

6 Photoautotroph is any being capable of generating its food from mineral material by photosynthesis under the action of sunlight.

7 The cyanobacteria are also known, although wrongly, as blue-green algae.

8 Chert is a hard, compact and dense sedimentary rock, consisting dominantly of cryptocrystalline and/or amorphous silica.

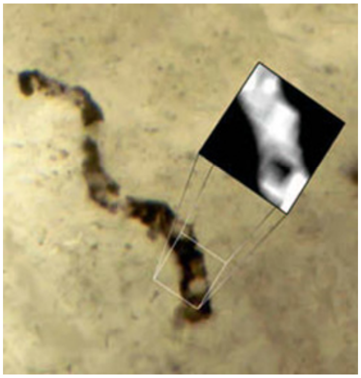


Fig. 5
Photographic image and laser Raman image (inset) of ~3.47 billion year-old microfossil from the Apex chert of Western Australia.
Credit: NASA / UCLA.
URL: http://www.astrobiology.ucla.edu/pages/res3e.html

Figure 2 shows a version of what is commonly referred to as the "Geological Clock", which is essentially a quadrant graduated from 0 to 5 Gyr. The period of time between 0 and 0.54 Gyr begins in the present today and ends on the Lower Cambrian,[9] when the first microfossils appear. We call this period "Biological Evolution" and it was then that cell differentiation took place until the emergence of Man and human intelligence. From the Lower Cambrian until the Early Archaean,[10] i.e. from 0.54 to about 3.8 Gyr, the Earth would have been inhabited only by unicellular beings mostly of the cyanobacteria type, with the most advanced forms grouped into colonies and often associated with seaweed. Throughout this period of time the changes would have occurred only at the cellular level, involving mainly metabolic mechanisms leading to biochemical and molecular differentiation, and speciation.[11] This we call "Biochemical Evolution".

Before the Archaean eon no fossils are found and evidence of Life is scarce and conjectural. Considering the estimated age of our planet and the fact that some form of Life existed 3.8 Gyr ago, little more than 0.7 Gyr remains for the formation of all chemical materials essential for generating the first metabolic processes. From the above evidence, everything seems to indicate that Life arose on Earth just after the period of cooling and consolidation, when the recently formed crust was still thin and very unstable, and bombarded by intense falls of meteorites and subject to violent volcanic eruptions. It seems thus likely that these highly unfavorable conditions led to some forms of "simple" life, which having emerged several times were subsequently destroyed. Even assuming that

9 The Cambrian period represents the start of the Paleozoic era and lasted since about 0.5 to 0.6 Gyr.

10 The age of the Earth is divided into four phases, called eons; they have the names Hadean (between the origin of the Earth and 3.8 Gyr), the Archaean (or Archean) (between 3.8 and 2.5 Gyr), the Proterozoic (between 2.5 and 0.54 Gyr) and Phanerozoic (from 0.54 Gyr until now). The latter comprises the Paleozoic, Mesozoic and Cenozoic eras.

11 Speciation is the process by which a living species gives rise to another species different from itself.

these early forms of Life were very primitive, minimal conditions of habitability would have been required, such as a solid crust and the existence of water to act as a liquid solvent medium for the occurrence of chemical reactions essential for Life. Very recently, inherited zircons[12] older than the 4.4 Gyr have been discovered, suggesting that at that time a solid crust already existed.

In conclusion, there is a period of about 0.6 Gyr with no fossil traces, at the end of which probably the first forms of Life had already emerged. How did they emerge? Were they generated spontaneously, or did they come from beyond the Earth? If they were spontaneously generated in a comparatively short period of time, it seems that there should exist complex chemical materials such as proteins and nucleic acids. In that case, how did they form? These are questions that remain open, despite numerous attempts to answer them, but great progress has been achieved in recent years. We will now review briefly the most significant of these conjectures.

12 Zircons are zirconium orthosilicates that crystallize in the tetragonal system and appear in various colors; the inherited zircons consist of inclusions in other minerals.

Chapter 2

Classical theories of Life's origins

The ways in which the trees and plants are originated are these: spontaneous generation, growth in seeds, by root [...].[1]

Fig. 6
Beetle of the Temple of Karnak, Egypt. The beetle was a symbol of spontaneous generation, of resurrection and of eternal life.

LIKE OURSELVES TODAY, OUR ANCESTORS HAVE always questioned how the World began. Lacking knowledge and often open-mindedness to find a rational answer as we nowadays seek, their thinking appeared in the form of legends, stories or mysterious struggles between Gods. It is in this environment that the message of the Christian religion emerged, presenting the World as the work of Jehovah, the living God — "Shapeless Earth... empty... darkness". Amid the primordial chaos, was the dynamic spirit of God.

2.1 Spontaneous Generation

THE FIRST SIMPLISTIC THEORY CONCERNING THE origin of Life appears in ancient Greece in the fourth century BC, with Aristotle (384 BC–322 BC), who gathered information from the most important countries, such as China, Babylon and Egypt. In some cases he checked

1 Theophrastus (371–287 BC), "Enquiry into Plants", vol. 1, p. 105.

it according to his own method and then produced what came to be the first scientific theory on the origin of Life — the theory of spontaneous generation. The idea of spontaneous generation remained for almost two thousand years and has strongly influenced many areas of knowledge, and has contributed significantly to the direction in which Western society has developed. It has even become adopted as the official doctrine for a scientific interpretation of the origin and evolution of Life by merging with the creationist concepts supported by the Church. This is most unexpected since Aristotle was a polytheist.

According to the theory of spontaneous generation some living beings could be created from inert matter, without any involvement with a pre-existing body. Regarding the matter that would emerge, there are two possibilities, *viz*. abiogenesis, the production of living organisms from inorganic matter, and heterogenesis, the formation of living organisms from organic but inert matter. These two versions have in common the fact that they do not involve any genetic continuity. There would have been two principles according to which Life could originate, a passive one, relating to inanimate matter, and an active one, acting on the passive principle with the power to shape the inanimate matter; under favorable conditions they would combine to generate Life. Living organisms generated in this way could be simple or complex, but would always arise suddenly and spontaneously. It was also believed that, as an alternative to sexual reproduction, under certain circumstances living beings could be formed from inert matter.

The idea of spontaneous generation was initially suggested by the daily and imprecise observation of how certain types of Life, apparently the most "simple", appeared in environments such as soil and water and, especially, in decomposing substances. It was such an established theory, that during Antiquity, the Middle Ages and even during the Modern Period, it had many illustrious supporters in ancient Greece such as Thales of Miletus (ca. 624–546 BC), Plato of Athens (428 / 27–347 BC), Epicurus of Samos (341–270 BC) and Democritus of Abdera (ca. 624–546 BC), together with St. Augustine of Tagasta (354–430) in Tunisia, St. Thomas Aquinas (1227–1274) in Italy, Paracelsus (1493–1541) in Switzerland, Nicolaus Copernicus (1473–1543) in Poland, Galileo Galilei (1564–1642) in Italy, Francis Bacon (1561–1626) in England, René Descartes (1596–1650) in France, Isaac Newton (1643–1727) also in England and Johann Wolfgang von Goethe (1749–1832) in Germany, amongst many others. Texts describing the formation of living beings from diverse forms of inert matter such as iodine, dew and stones are abundant!

There were actual recipes to produce the most different types of living beings, from small insects and worms to crocodiles, using, typically, amongst other "ingredients", organic matter in putrefaction. Of these, one may highlight the well-known "recipe" of the physician Johann Baptist van Helmont (1577–1644) to produce mice from wheat and dirty clothes, which when mixed together in a container would, twenty-one days later, give rise to adult and fully shaped rats. In the light of what we know today, we can say that Helmont conducted his experiment in an uncontrolled way: the fact that the container remained open during the 21 days when this occurred, allowing these animals to go inside, where they fed on the existing wheat and procreated. However, this went unnoticed to the thinkers of that time!

Francesco Redi's experiment

In an open container Redi placed meat of a recently dead animal. After a few days, he noticed the appearance of eggs on meat undergoing putrefaction, which were later transformed into larvae and these into flies. Faced with this result, he prepared a new piece of fresh meat and divided it into two portions; one of them was put inside a container covered with gauze and the other in another container that he covered with

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Fig. 7
Illustration of Redi's experiment.

a cloth. In the container covered with gauze the flies deposited eggs on the gauze, but there were no larvae in the meat; in the container covered with cloth no eggs or larvae or flies appeared. Thus, he concluded that in the case of the open container the flies deposited their eggs on the meat, which subsequently gave rise to the larvae, whereas in the covered containers the meat was protected from flies and formation of larvae was not observed.

One of the first opponents to the "official theory" of spontaneous generation was the Florentine physician and biologist Francesco Redi (1626–1697), and it was through him that this theory began to lose credibility. Indeed, in 1668 Redi had performed experiments proving that the larvae appearing in the meat under putrefaction came from the eggs of the flies that set upon it and were not caused by spontaneous generation, i.e. did not derive from the meat (Fig. 7). However, this simple experiment carried out by Redi was not original, as it had already been performed by others, but the conclusions he reached were indeed novel. In fact, he showed that larvae appear only when the flies were able to deposit eggs on the meat and

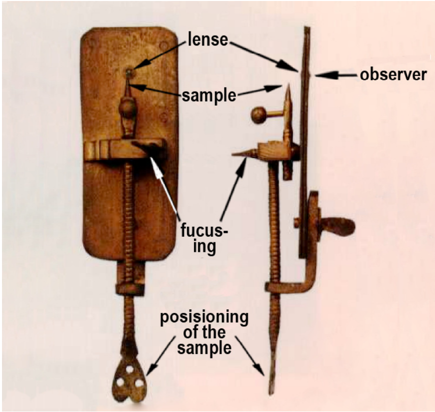

Fig. 8
Antoni Van Leeuwenhoek's microscope.

therefore the belief in spontaneous generation was simply a consequence of faulty observation. This conclusion shook the theory, but was not enough to overthrow it, as we shall see below.

At the end of the seventeenth century the optical microscope was in widespread use thanks to the work of Antoni van Leeuwenhoek (1632–1723). This businessman from Delft, in The Netherlands, spent a good part of his time not only building often rudimentary microscopes, but improving and utilizing them (Fig. 8). He discovered a new "world" of microscopic beings, hitherto unknown, and encouraged others to share his observations. His instruments allowed the observation of microorganisms in any sample of matter in putrefaction, showing that beings of minute size could be generated by spontaneous generation and not by reproduction. Leeuwenhoek's discoveries of the microscopic world added impetus to the survival of the theory of spontaneous generation and added to confusion by encouraging controversy between the theory's supporters and its critics. In fact, the scientific community remained divided on this issue until the mid-nineteenth century. During the seventeenth and eighteenth centuries, there were many who tried to disprove spontaneous generation, but none managed to prove their ideas conclusively.

A century after Redi, in a polemical argument on the spontaneous generation between the English biologist John Needham (1713–1781) and the Italian priest and biologist Lazzaro Spallanzani (1729–1799) another step was taken towards the refutation of this theory. Spalanzani was of the opinion that microorganisms that infest a broth exposed to the air came from the air itself; thus, he showed that by boiling the broth in a closed container the microorganisms are destroyed and the broth stays sterile. However, Needham argued that air was vital to Life and, because Spallanzani had excluded air, the heating had destroyed the "vital force". A further century had to elapse before this controversy was resolved definitively!

The spontaneous generation of Life from inorganic materials became an "Achilles heel" as it challenged the concept of a "vital force" (vitalism), which was entrenched in the minds of thinkers as being the cause of spontaneous generation. This concept distinguished

Fig. 9
From left to right: Friedrich Wöhler, Adolph W.H. Kolbe and Adolph Strecker.

the inorganic from the organic states, and the transformation of the mineral world into the living world — creation of living organisms from inert matter — would imply mastering this force. It implied that without overcoming this "vital force", it would be impossible to obtain organic compounds, i.e. chemical compounds related to living beings. This belief was broken only in 1828, when, by sheer serendipity, Friedrich Wöhler (1800–1882) synthesized urea from inorganic chemicals. In 1845, vitalism was struck another blow with the synthesis of acetic acid by Adolph W.H. Kolbe (1818–1884) and five years later, in 1850, it was dealt a further blow by another German chemist, Adolph Strecker (1822–1871), with the synthesis of the amino acid, alanine.

With the fall of the "vital force" taboo the issue of spontaneous generation regained strength, and was only completely and definitively rejected in 1864 by the work of Louis

Fig. 10
From left to right: Louis Pateur, Pasteur's experiment and Félix-Archimède Pouchet

Pasteur (1822–1895), carried out with great accuracy and mastery by this famous French chemist and biologist. He exposed previously boiled broth to air, but protected it with a filter to prevent contamination with particles in the air and found that while the filter was highly contaminated by microorganisms, the broth remained sterile. He also showed that the broth remained sterile inside a glass container even when open, provided that it possessed a restriction in the form of an S bend or swan neck to prevent the microorganisms in the air from coming into contact with the broth. This discovery had been preceded by an intense debate between Pasteur and Felix-Archimède Pouchet (1800–1872), the last of the major defenders of the theory of spontaneous generation. In 1881, in England, John Tyndall (1820–1893) later demonstrated that some bacteria were resistant to high temperatures, and thus able to reproduce again after some heating, which would explain why at first glance certain observations appeared to corroborate the theory of spontaneous generation.

At this point it is pertinent to mention that Pasteur's experiments showed that spontaneous generation should not occur under the present conditions of the Earth. However, if all living beings come from other pre-existing living beings, how could the first living beings have given rise to others? How did Life appear for the first time? This basic question remains unanswered.

2.2 Creationism

In the beginning, God created the heaven and the earth. And the earth was without form and void. And darkness was upon the face of the deep. And the Spirit of God moved upon the face of the waters.[2]

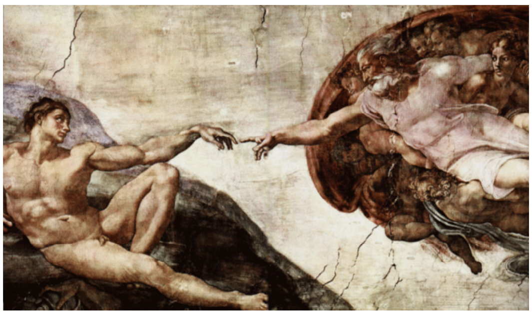

Fig. 11
"God creates Adam" (1510)
by Michelangelo Buonarroti (1475–1564).
Sistine Chapel, Vatican.

HISTORICALLY, FOSSILS WERE ALWAYS DIRECTLY or indirectly related to the origin of Life, and the creation of living beings. During the Middle Ages the official teachings of scholasticism were mainly governed by the Aristotelian dictates, mainly through the rediscovery of

2 This is the sentence that begins the holy book that recounts the Creation of the World — the book of Genesis, whose first page is an ode to Creation.

the classics during the Arabic expansion. For St. Albert the Great (1193–1280) and Giovanni Boccaccio (1313–1375), the origin of living fossils resided in the 'forming quality' (*virtus formativa*), similar to what Avicenna[3] (980–1037), an Arab physician, had previously mentioned as 'primitive mud with a capacity to create stony shapes, without Life'.

It was this line of reasoning that in the West gave rise to Creationism, a chain of philosophical knowledge that remained rooted throughout the Renaissance and had several important persons as its main proponents, each offering their own interpretation of the origin and significance of fossils. Thus, Karl Gessner (1516–1565) called them the "pictures of stone" (*lapides figurati*) and Martin Lister (1638–1712) called them "special stones" (*lapides sui generis*). More expressive was the name they were given by Edward Lhwyd (1660–1709), i.e. "breath of life" (*aura seminalis*). Later, Karl Georg von Raumer (1783–1865) argued that fossils were creative failures of nature, species that never came to life, whilst a contemporary, Alcide d'Orbigny (1802–1857) believed that each geological stratum corresponded to a new creation.

However, not all thinkers had such strange ideas about fossils. Indeed, in the seventeenth century in Denmark, Nicholas Steno (1638–1686) believed that the *lapides figurati* were not God's failed attempts in the Creation act, as many believed, but that they were really marks of bodies that lived a long time ago and were now extinct. The growing awareness of the existence of forms that result from extinct fossil species has shaken some more fundamental creationist convictions, particularly those based on the belief that there were several Creations, with extinct species reflecting the natural order of things, and being possible exemplars of their Creator's failures.

Christian religions used to defend, and some still do, ideas about the origin of all things including living creatures being based on a unique creation event. These ideas, resulting directly from the literal interpretation of the Book of Genesis, showed contradictions that have become increasingly significant as, over time, scientific knowledge has grown and gained ground in the minds of thinkers. Evolution of human mentality and development of scientific knowledge have led many thinkers to reflect on the literal truthfulness of what is written in the Bible concerning God's creation of Life, in a single event of Creation. Most moderates now question the value of literal interpretations of the Bible and other sacred texts on the origins of Life that were, and still are, made by many. However, the resulting absence of a divine hand in creation caused a void in thinking which led to new hypotheses and attempts to answer this question, among which is the resurgence of abiogenesis or spontaneous generation

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3 Abu Ali al-Hussayn ibn Abd-Allah ibn Sina was known in the West as Avicenna.

Chapter 3

Evolutionism

Nothing is immutable, everything changes.[1]

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Fig. 12
Illustration of the concept that Life started in the water, explored by M.C. Escher (1898-1972) in his well known artwork "Sky and Water" (1938).

The first evolutionist ideas, initially called transformist ideas, established that Life has a long and continuing history during which time the animal and plant organisms are changing and populating the Earth. Denied immediate experience, but supported by the observation and peaceful reflection of things, the idea that the world evolved had germinated in ancient Greece. One of the first records comes to us from Anaximander (610–547 BC), but others have followed him such as Heraclitus (540–480 BC), Empedocles (492–432 BC), Xenophanes (384–322 BC) and Aristotle (384–322 BC). After the Greek decline and the subsequent flourishing of the Roman Empire, the texts left by these philosophers have been ignored, mainly because they failed to adjust to the pragmatism of Rome. Only later, during the Roman decline and the flourishing expansion of the Arab civilization, did the works of the great Greek thinkers become reinstated

1 Heraclitus of Ephesus, of Ionia (540–470 BC).

from oblivion. And it was by translation from Arabic to Latin that they finally arrived in Rome and the rest of Europe, that were already experiencing the Renaissance. However, their arrival was not always peaceful, the parts that did not conform to the fixed and creationist doctrines of Church being censored along with those who supported them. This happened to Giordano Bruno (1548–1600), a Dominican monk, philosopher and poet, who defended the evolution of the World, but was burned in the fire of the Holy Office.

Less than half a century later, René Descartes (1596–1650) writing in his mother tongue, French, rather than Latin, the official language of the Roman church, expressed the opinion that the World and those living in it, had evolved. But, being a Catholic, Descartes did not undervalue God's potentiality, assigning to him instead, the supreme power of defining the laws that would govern evolution and the creation of all human beings without having concern about the details of Creation. Thus, Western civilization began to divide itself into two factions, the followers of the doctrines of Christian Churches and those that were God-fearing, but non-believers of literal interpretations of the Bible. Throughout the Renaissance one moves from a concept of an immutable Nature, governed by fixity of vision, to a model that considers that Nature is subject to change. From the eighteenth century onwards this dual perception of the world disturbed the conscience of those who engaged in its study and reflection, as the World revealed itself to them as a reality far from being immutable, but suggesting permanent changes. Two areas of knowledge that contributed decisively to the transition from fixism to evolutionism were the study of presently living species and the detailed analysis of fossils.

Many naturalists contributed to the development of a theory of evolution of living beings, some more than others. To explain fossils, Nicholas Steno, the Danish Catholic priest (mentioned in 2.2 above), proposed around 1685 that species could change over time. In his book *Historia Plantarum*, published in England in 1686, John Ray (1627–1705) defined "species" on the basis of a common ancestor (Fig. 13). In 1735 Carolus Linnaeus (1707–1778), the famous Swedish naturalist, published a book, *Systema Naturae,* that is still used today in which he described the methodology for the classification of all organisms; Linnaeus believed that, within a given genus, species are generated by hybridization, although only under the control of God's hand. In 1741, in France, Pierre-Louis Moreau de Maupertuis (1698–1759) in his book "Essai de Cosmologie" maintained that the strongest animals produced more children, thereby strengthening the species, a form of natural selection. Also in France in 1749, when publishing his extensive work "Histoire Naturelle" the Count of Buffon, or George Louis Leclerc (1707–1788), affirmed that living beings evolve, but, apparently because he feared the Church, left no more than a brief sketch of his idea. In his "La palingénésie philosophique", published in 1770, the Swiss naturalist Charles Bonnet (1720–1793) suggested that disasters caused evolutionary changes, stating that: "In the next natural disaster living beings rise one more step on the evolution scale, the men being transformed into angels, the primates into men and so on". Four years later, the physician,

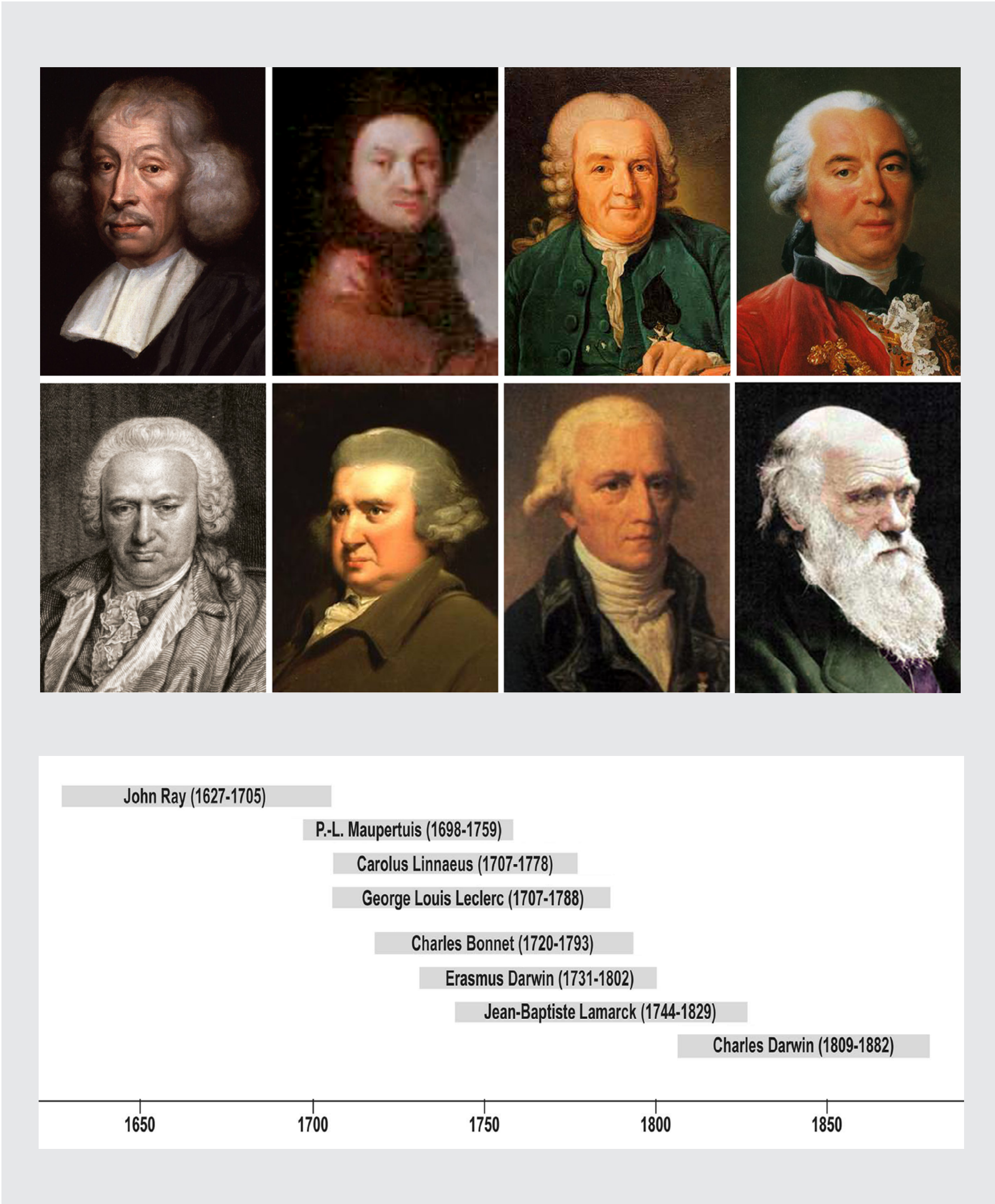

Fig. 13
Pioneers of the Theory of Evolution.
From left to right, starting on top: John Ray, Pierre-Louis Moreau de Maupertuis, Carolus Linnaeus, George Louis Leclerc, Charles Bonnet, Erasmus Darwin, Jean-Baptiste Lamarck and Charles Darwin.

poet and English naturalist Erasmus Darwin (1731–1802), grandfather of Charles Darwin, published "Zoonomia", which argues that all species come from a common ancestor and that speciation has occurred through time by competition and sexual selection, but the author did not present any facts supporting this theory. The first explanatory theory based on the mechanisms of evolution of living beings appeared in 1809 with Jean-Baptiste Lamarck (1744–1829) and became known as Lamarckism. However, the paradigmatic revolution that led to the replacement of the fixed by the evolutionary model, occurred with Charles Darwin (1809–1882), especially after the publication of his famous book "On the Origin of Species" in 1859.

3.1 Lamarckism

All that Nature has allowed individuals to gain or lose by the influence of the circumstances to which their race has been exposed for a long time, and consequently, by the effect of predominant use of such body, or by a defect resulting from the use of such part, is conserved for the new individuals that would come by reproduction, provided that the acquired changes are common to both sexes, or to those who produced these new individuals.[2]

Fig. 14
Usage develops the organ.

According to Lamarck, living beings show changes that depend on the environment in which they develop. The environment affects changes, leading to the emergence of features that enable individuals to adapt to the conditions in which they live. The adaptation would therefore represent the ability of all living beings to develop structural or functional characteristics to survive and reproduce in a given environment. To explain the existence of evolution this brilliant naturalist proposed four laws, which can be briefly described as follows.

2 Jean-Baptiste Lamarck (1744–1829), 1809.

1 Living beings and their parts tend to rise gradually in size.
2 Production of a new organ in a living being follows the emergence of a new need or desire.
3 The use of any organ leads to its development, while disuse leads to its atrophy.
4 The characteristics gained or lost by a living being tend to be transmitted by heredity.

Many authors summarize these four laws in two fundamental principles, namely the principle of use and disuse (3rd law) and the principle of inheritance of acquired characteristics (4th law), the first two laws being discarded because they are too unlikely. The changes that would lead to adaptation are explained by the law of use and disuse. According to this law, the need for a body in a specific environment creates this body and its function modifies it. Thus, if an organ is very much used it develops, becoming stronger, more vigorous or larger in size; if, on the contrary, the organ is not used, it degenerates and atrophies. According to the law of inheritance of acquired characteristics, the changes that occur in individuals throughout their life as a consequence of the use or disuse of organs would be hereditary, resulting in morphological changes in the whole population. The inheritance of acquired characteristics, as it became known, is a simple and pragmatic explanation. By the need to adapt to the environment, organisms acquire changes during their life, which would be passed on to descendants. Adaptation would be gradual and an organism could develop any such adaptation, as long as it were necessary, species moving in this way to perfect harmony with their environment.

Lamarck's model was much contested because it proposes an explanation that gives evolution an intention or purpose, changes occurring as a result of species seeking their "best" design; but inheritance of acquired characteristics could not be proved experimentally. August Weismann (1834–1914) tried to prove it by an experiment in 1880 in which he cut the tails of a group of white mice, and found that their descendants all presented tails with normal length. He repeated this procedure over twenty-two generations, always obtaining offspring with normal tails. Today, although one recognizes that the use and disuse of certain organs does affect its development, it is thought that these characteristics are not transmitted to descendants. However, we will see later that recent discoveries in the field of Genomics[3] have led to a fundamental review of the possibility of hereditary transmission of acquired characteristics by influence of the environment or of circumstances related to it or depending on it, but independent of the individual's will or intention, or of any tendency towards perfection.

3 Science that deals with the determination of genomes, i.e. the nucleotide sequence of the DNA of living species.

3.2 Darwinism

Nothing in Biology makes sense except in the light of evolution.[4]

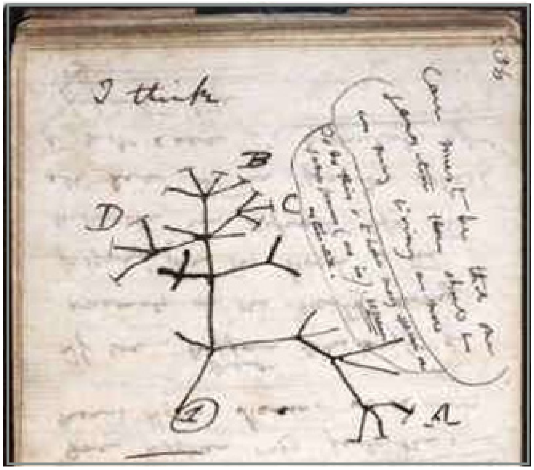

Fig. 15
Charles Darwin's Tree of Life.
http://geopolicraticus.wordpress.com/2009/04/28/quantifying-biological-success/

THE QUESTION "HOW DID LIFE APPEAR FOR the first time" won notoriety with the publication in 1859, of Charles Darwin's book "On the Origin of Species by Means of Natural Selection or the Preservation of Favored Races in the Struggle for Life". This publication had great scientific, social and religious impact, as it proposed a truly rational mechanism to evolution, and particularly because it was based on very extensive, rigorous and discerning observation of living species. It implied that all today's living beings were the result of a long biological evolution by natural selection from a very simple primitive organism. Darwin was innovative because he explained how beings had differentiated and evolved and not for the general idea of evolution; this had already been proposed before him by Lamarck and indeed by his grandfather Erasmus Darwin. Darwin was hastened to publication, after many years deliberating his theory, by a letter written to him by Alfred Russel Wallace (1823–1913) in 1858, which contained essentially the same idea of evolution by natural selection. It was agreed that Darwin and Wallace would present a joint paper to the Linnean Society in the same year, which indeed happened, and this was followed in 1859 by Darwin's master work.

Darwin undermined the ideas that prevailed at that time that supported a perfectly shaped and harmonious natural world, and replaced it with the concept of struggle of species for survival against attack by their environment in a process that came to be called natural selection. The notions of progress and perfection were shaken by the demonstration that evo-

4 Theodosius G. Dobzhansky (1900–1975), *The American Biology Teacher, 35* (1973) 125–129.

lution implies change and adjustment, and not necessarily leads to progress and never to perfection. Nevertheless, Darwin was always very cautious and moderate in the terms he used to describe his ideas, mentioning only random variation and natural selection. In fact, the concept of "survival of the fittest", suggested by the English philosopher Herbert Spencer (1820–1903), only appeared in the fifth edition of his book, ten years after the first edition, and only in the sixth edition of 1872, was the word "evolution" mentioned. Darwin laid the first foundations for a genuine theory of evolution, but there were others who extended the concept of "Darwinism", to establish new bases for philosophical thought far beyond Biology. Indeed, Darwinism has led to acceptable influences in Socialist and Marxist doctrines, but on the other hand has led to deplorable ideas such as eugenics.[5]

Darwin introduced the concept of common origin, i.e. the diversification of species according to the logic of an irregularly branched tree, thus contradicting the belief in the creation of each individual species, and established in its place the concept that all Life descended from a common ancestor. The importance of this idea was such that in orthodox scientific circles the concept of evolution that all organisms on Earth are descended from a single source is now universally accepted. Darwin put an end to the idea that man was the product of a special creation, but, on the contrary, was a product of evolution in accordance with principles that apply to the rest of the living world. Darwin thus offered an explanation for the mechanism of evolution of species that was completely innovative and broke with the dominant thought at that time. Some authors argue that Darwin's theory formed the basis of a restructuring of all areas of Biology. Paleontology, which until then was limited to describing and systematizing data concerning extinct animals and plants, began to include the study of the phylogenies[6] of development of the organic world; animal and plant Systematics began including investigations into kinship links and the origin of the groups of living beings; Embryologists began recognizing the common steps in the development of the organisms during the process of maturation; and Physiologists began to engage in the comparative study of vital activity of humans and other animals and to establish links of kinship between them. At the beginning of the twentieth century, the effects of natural selection began to be investigated experimentally, giving great impetus to research in Ecology, Genetics, and many other areas of Biological Sciences.

Although at the time Darwin's theory had a huge impact, it did have some shortcomings; it is fair to admit that the theory did not contain an adequate explanation for the inheritance of characteristics. This was due to the lack of scientific knowledge, namely the assumptions of Mendelian genetics, that were not yet known. One must allow for the fact that, at the time, it was not possible to properly explain genetic variability; what is known today about the mechanisms of speciation resulted from the development of new scientific disciplines. It was in 1865, that the monk Gregor Mendel (1822–1884), from Brno, Austria (now the Czech Republic), published the key to understanding the nature of variability. This was an issue ap-

5 Eugenics is a movement of thought that advocates the improvement of the human race by methods related to birth control; it is the most recognized theoretical basis for the development of racist movements.

6 Phylogeny is the study of relationships between the position of simple Life forms and that of complex ones in the tree of evolution (*cf*. Fig. 1).

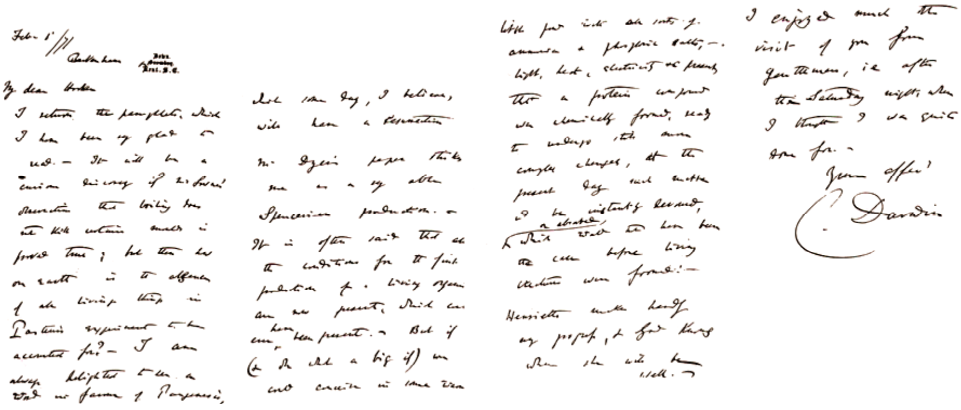

Fig. 16
Letter sent by Charles Darwin to Joseph Hooker in February 1871
[in H. Hartman, J.G. Lawless and P. Morrison (eds.), *Search for the Universal Ancestors*, Ames Research Center, NASA, Washington, 1985].

parently unknown to Darwin, but one that might have explained the various questions that have arisen about the nature of variability and natural selection acting on it. Most probably the English biologist was not aware of the work of the Austrian monk since, ironically, it was only after Darwin's death that, according to some authors, a letter sent by Mendel containing copies of his work was found among Darwin's papers but unopened!

It is notable that an explanation for the emergence of that initial "being" from which all others had developed was still missing. At that time this was not of great importance, since the likelihood of existing spontaneous generation was still being discussed. It is clear that evolutionism did not answer this question, but only raised it by suggesting a possible way towards an answer. Darwin never published anything about the origin of Life, but in a letter (Fig. 16) sent to his friend Joseph Hooker (1814–1889) in February 1871, he makes some comments that reflect his interest in the subject and, above all, reflect concepts close to those that, some fifty years later, would be developed and published by Aleksandr Oparin (1894–1980) and John Haldane (1892–1964). These considerations involved chemical evolution under physical and chemical conditions different from those existing at present: "*But if (and oh, what a big if) we could conceive in some little pond, with all sorts of ammonia and phosphoric salts, light, heat, electricity, etc., present, that a protein compound was chemically formed, ready to undergo still more complex changes, at present day such matter would be instantly devoured or absorbed, which would not have been the case before living creatures were formed*". It should be remarked that the non-existence of spontaneous generation had been vindicated only seven years earlier. It is noteworthy that, ten years after the above letter was written by Darwin, John Tyndall (1820–1893) in England showed that some bacteria were resistant to high temperatures, being able to undergo subsequent reproduction. This observation may explain why John Needham, in his argument with Spallanzani defended the existence of spontaneous generation with such staunchness.

Despite the gaps left by the contributions of Lamarck and Darwin, the idea of evolution became firmly established within the scientific community. Results of observations and studies carried out since the nineteenth century until today continue to be consistent — and we would even risk saying 'the only ones that are consistent'— with evolutionism, new data strengthening and refining the concept of "Darwinian evolution".

3.3 Neo-Lamarckism and Neo-Darwinism

When a distinguished but elderly scientist states that something is possible, he is almost certainly right. When he states that something is impossible, he is very probably wrong.[7]

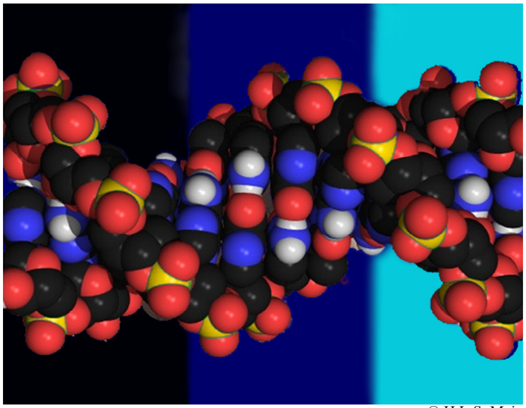

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Fig. 17
Molecular model of a DNA segment.

AMONG THE CURRENT THEORIES IN BIOLOGY regarding the mechanisms of evolution, there is one that is known as "Neo-Lamarckism". Although its followers represent a minority, they believe that the environment can shape and modify the individual. They consider it possible that cytoplasmic[8] proteins that can be modified by their environment may act on the DNA, so altering it. Thus, they try to interpret the concepts of Lamarck in the light of current data of Molecular Genetics, thereby ensuring the survival of the old model. They recognize, however, that only changes that occur at the level of the genetic material of the gametes[9] are passed on to descendants. The term Neo-Lamarckism was first used by Edward D. Cope (1840–1897), an American paleontologist, but is much popularized by the French School of thought which has strong cultural links to Lamarck.

7 "Clarke's First Law", Arthur C. Clarke (1917–2008).
8 Cytoplasm is the material contained in the cells between the membrane and the nucleus.
9 Gamete is a mature reproductive cell, such as the egg or the spermatozoid.

The 1930s were characterized by intense debates about the evolution of species. It was then that researchers confronted the original ideas of Darwin with data that had subsequently emerged in Genetics, Paleontology, Biogeography, Embryology and also in Ethology.[10] Since this confrontation, Darwinian theory has been refined and explained in the light of these new disciplines, leading to the emergence of the new theory, Neo-Darwinism, which also goes under the name Synthetic Theory of Evolution (hereinafter referred to as STE). Although the ideas of STE had emerged some years earlier, this

Fig. 18
Thomas Huxley (left) with his grandson Julian in 1895 (center) and Julian Huxley in 1922 (right).

name was in fact introduced in 1942 by the English evolutionary biologist Julian Huxley (1887–1975) in his book “Evolution: the modern synthesis” and consists of two fundamental concepts, genetic variability and natural selection. Julian Huxley was brother of the well known writer Aldous Huxley (1894–1963) and half-brother of Andrew Huxley (1917–), who received the Nobel Prize in Physiology or Medicine in 1963; they were grandchildren of the evolutionary biologist Thomas Huxley (1825–1895), who was a great friend and unconditional admirer of Darwin, and the main proponent of Darwinian theory applied to humans.

As mentioned above, the theory of evolution by natural selection as outlined by Darwin had some weak points. Indeed, the mechanisms responsible for the observed variations in the species and the way these variations pass from generation to generation remained unexplained. Already in Darwin’s time the question as to whether evolution occurred by gradual changes or by mutations was a matter of debate and controversy and has remained so. After the explosion of knowledge in Genetics that took place over the last century, experts now seem inclined to accept both mechanisms. While Mendelian speciation provided by genetic recombination associated with sexual reproduction

10 The science that deals with the compared behavior of living beings.

provides a mechanism for gradual evolution, the concept of genetic mutation made it possible to consider mutations at the gene[11] level as a further important source of speciation.

It is now found that the genome[12] may experience many abrupt changes, or mutations, which can occur either at the level of genes, or at the level of chromosomes,[13] Many mutations have a disastrous effect and the affected individuals tend to disappear. In other cases, however, they may have a favorable effect and allow their carriers to live longer and reproduce more. Mutations are the primary source of genetic variability, introducing new genes in populations. The speciation generated by recombination of genes through sexual reproduction can occur at different times, i.e. both in meiosis[14] and in fertilization. Thus, one may conclude that mutations introduce genetic novelty, but it is mainly genetic recombination that creates variability, favoring the emergence of a multitude of different gene combinations.

Natural selection does not act on genes or on genetic characteristics alone, but on individuals with their total genetic load, human and otherwise; selection requires advantageous combinations of several gene sets. Each gene set confers certain adaptive capabilities to individuals for a given environment and at a given time. The individual who has the most advantageous combination of characteristics will be selected in preference to the less advantaged. The greater the diversity, the greater the likelihood of a population to adapt to changes occurring in this environment, because amongst all this diversity a given gene set favored by natural selection may appear. Very homogeneous and well-adjusted populations may be eliminated if any significant change occurs in their habitat such as, for example, climate change. When the characteristics of the environment change, the most favorable gene set may sometimes become unfavorable in the new environment; thus, what is most likely to survive varies in space and time, according to specific environmental conditions.

In summary, one may conclude that, together with gene recombination that occurs in sexual reproduction, mutations responsible for the emergence of new genes in the gene pool of populations lead to their genetic variability. It is on this variability that the natural selection operates, favoring those gene sets that are better adapted to a particular environment at a given time. Individuals that hold these gene sets will live longer and leave more descendents, thus giving rise to differential reproduction. Over time, certain genes, and therefore certain characteristics, get implanted at the expense of others that will be gradually eliminated, thus generating evolution.

Despite being constantly refined and updated, the STE, although commanding far greater acceptance nowadays, still does not explain evolution in a way that fully satisfies all

11 Gene is any segment of DNA that contains coded instructions for synthesis of a given RNA, which when translated into a protein, leads to the expression of a hereditary character.

12 Genome is the set of chromosomes of a given living being.

13 Chromosomes are filamentous bodies, long DNA chains, where the genes are arranged linearly.

14 Meiosis is the process connected with reproduction, which is a cell division in which each cell gets half its previous number of chromosomes.

parties within scientific circles. The "architects" of STE and their followers believe that the conceptual changes, the new discoveries and the advances that emerged during the 1930–1980 period are just elaborations or additions to the classical theory that was formulated in the 1940s. Those faithful to Darwin raise objections to this "new" way to interpret evolution, as they believe that the evolutionary theory has diversified its territory too much, and that different levels of evolutionary change may result from different causes. One must consider also all those who argue that recent scientific data show totally new phenomena that consequently do not fit the original Darwinist concepts. So, other theories have been emerging in opposition to the STE, providing a different interpretation of the available data and giving a greater or lesser value to certain aspects according to the precise scientific issue under consideration.

In recent times, these new theories have created an expansion in the impact of evolutionary theory. The study of molecular evolution has introduced ideas that are alternatives to natural selection. The discovery, by the American geneticist Barbara McClintock (1902–1992), Nobel Prize winner in Physiology or Medicine in 1983, of inserted sequences of "jumping genes"[15] not only increased the complexity of genetic research, but also brought about new evolutionary puzzles. Another issue is the unidirectionality of the genotype/phenotype,[16] i.e. the phenotype, which receives the selective pressure of the environment without interfering with the genotype. Admitting the contrary would mean accepting the inheritance of acquired characters. However, the knowledge of structural and regulatory genes[17] raises questions regarding this unidirectionality. While the structural genes are inflexible to environmental variations, the regulators, which are responsible for regulating the time, the performance and the deactivation of the structural genes, seem to be much more flexible. This opens up the possibility that the regulatory genes will be sensitive to environmental pressure on the phenotype. All this jeopardizes many of the general postulates of STE.

As a result of such influences introduced by Molecular Biology, two types of direct conflict with the STE have arisen: firstly, the Neutralist Theory, proposed in the late 1960s by the Japanese geneticist Motoo Kimura (1924–1984), which is based on the claim that chance establishes not only the initial appearance of genetic variability, but also its later destination within the population; and, secondly, the neo-Lamarckism of Pierre-Paul Grassé (1895–1985), that proposes that variations in DNA can be due, to a greater or lesser degree, to a certain molecular determinism rather than to pure chance. It should also be borne in mind that Paleontology introduces another type of challenge, called Theory of Intermittent Equilibrium, or Punctualism, propounded by Stephen Jay Gould (1941–2002), that holds that evolution does not occur gradually, but in an erratic way, i.e. with jumps and convulsions.

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15 Usually each gene occupies a particular place in a DNA chain. The "jumping genes" are exceptions because they are characterized for being able to arise in different places.

16 Genotype is the set of genes of a living being, while the phenotype is the whole of the physical characteristics of that living being, directly related to its genotype.

17 The structural genes encode a protein for it to perform maintenance, metabolism, support or any other specialized function in the cell.

Chapter 4

Endogenous origin of Life — chemical theory

The present is the key to the past…[1]

Fig. 19
The Earth as photographed during a NASA mission.
Credit: NASA.
URL: http://actualidad.terra.es/articulo/html/av290264.htm

EXISTING LIVING BEINGS ARE GROUPED INTO two categories with regard to their mode of nutrition. Those that produce their organic matter solely from inorganic matter (water, carbon dioxide and minerals) by the action of sunlight or some other form of energy, chemical or otherwise, are called autotrophic. Those that feed directly or indirectly from autotrophic beings are called heterotrophic. It would seem, then, that the first forms of Life should be autotrophic. However, chlorophyll, the molecule that promotes photosynthesis in green plants, arose apparently only about 1 Gyr after the first forms of Life (*cf.* Fig. 2, "Geological Clock"), which is in accord with the fact that photosynthesis is a process that requires a very advanced level of organization and evolution. Therefore, the first living things were either (i) autotrophic, their metabolisms being assisted by forms of energy other than sunlight, or (ii) heterotrophic, "feed-

1 Concept attributed to James Hutton (1736–1797), Scottish geologist considered by many the father of modern Geology.

ing" from material generated in a process of chemical evolution already well developed, or (iii) came from outside the Earth together with such material/food. The first two options constitute the so-called Endogenous Hypothesis of Origin of Life, which we will describe in this chapter, while the third is the so-called Exogenous Hypothesis, with which we shall deal later. In all cases these early forms of Life would have been very rudimentary, acquiring complexity gradually in the course of time.

4.1 The Oparin-Haldane model

In the letter Darwin sent to Hooker in February 1871 he wondered about the possibility of one day Life appearing on our planet from chemical materials that were dissolved in the waters of a 'warm pool.' Nothing was then known about the existence of microfossils — the first ones were found only in the mid-twentieth century; also little was then known about the age of the Earth and of Life on this planet, and even less was known about how long it would have been needed for Life to arise or how long had elapsed between the consolidation of the planet and the appearance of the first living creatures. During the first half of last century it became established that the planet was more than 4 Gyr old, while the oldest known fossils would be about 0.6 Gyr old. Thus, it seemed that there had been plenty of time for our planet to generate conditions suitable for the emergence of the first living being from inanimate matter. This would entail a chemical origin based on abiotic production of increasingly complex organic molecules followed by evolution of these molecules towards Life as we know it.

During the 1920s, Aleksandr I. Oparin (1894–1980), in the Soviet Union, and John B.S. Haldane (1892–1964), in England, independently developed what became known as the Oparin-Haldane Hypothesis, a hypothesis for a heterotrophic origin, which Darwin's pioneering ideas had promoted. Their ideas were based on a prebiotic chemical evolution of the primitive Earth, which would culminate in the appearance of the first living creature. This model proposed a primitive atmosphere devoid or nearly devoid of oxygen and assumed that oceans or lakes al-

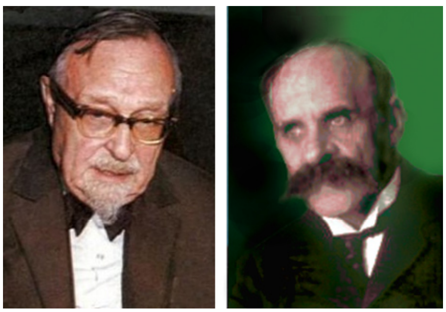


Fig. 20
Aleksandr Ivanovich Oparin and John Burdon Sanderson Haldane.

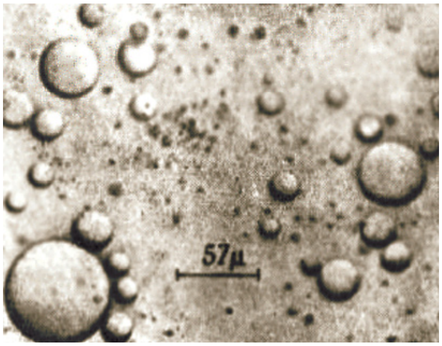


Fig. 21
Aleksandr Oparin's coacervates.
Credit: Cyril Ponnamperuma, *The Origin of Life*, E. P. Dutton & Co., 1972, p. 103.
URL: http://www.daviddarling.info/encyclopedia/C/coacervate.html

ready existed from the large amount of water vapor released by volcanic degassing of the planet. The sources of energy needed for the occurrence of chemical reactions had been supplied by the ultraviolet (UV) radiation emitted by the Sun, through electric discharges into the atmosphere during the violent storms that struck the early planet, and the heat released by volcanoes.

The compounds in the primitive reactive medium would provide all the necessary elements for the synthesis of organic compounds, with methane providing carbon, ammonia from which nitrogen would result, and water as the source of oxygen. The reactions of these primordial compounds would produce organic compounds that would accumulate in lakes and primitive seas, producing the so-called "primitive or primordial soup". In the course of thousands or millions of years these organic compounds would react with each other to lead to more and more complex organic molecules, such as amino acids[2] and sugars,[3] amongst others; in due time, these would form organic polymers such as proteins, which later would organize into more complex structures that Oparin called "coacervates" (Fig. 21). Coacervates were already known, but it was Oparin who stressed their possible importance in the origin of Life, since they could act as rudimentary cell membranes; such membranes would be essential for the separation of an external from an internal medium and thus allow a selective permeability. For years Oparin tested the occurrence of reactions inside these membranes, noting that they had the ability to grow and divide. He considered that they could have been the precursors of living cells, the sub-vital systems from which the first heterotrophic organisms would arise, organisms that would feed on the same "primordial soup" and would be anaerobic, in view of the lack of oxygen in the early atmosphere. The main criticism to Oparin's proposal is that the coacervates that he had used in his experiments were produced at the expense of organic matter from living species existing today such as gelatin and Arabic gum, without any support for the possibility of their existence at the start.

2 Amino acids are basic components of proteins and are synthesized in the living cells.
3 Sugars are essential to Life such as we know it, since they are found in RNA, in DNA, in cellulose and in other cellular components.

4.2 Experiments of synthesis under prebiotic conditions

At the start of the 1950s, Harold Urey (1893–1981), Professor of Astrochemistry at the University of Chicago and Nobel Prize winner of Chemistry in 1934, knowing the chemical composition of the outer planets of our solar system, argued that the primitive Earth's atmosphere should have been similar to the atmosphere of those outer planets, i.e. reductive.[4] Around that time, a young chemist called Stanley Miller (1930–2007) asked Urey if he would supervise him in post-graduate work leading to a doctorate. As a subject for this purpose Miller proposed the laboratory simulation of the physical and chemical conditions of the Earth after its consolidation, with the aim to test the Oparin-Haldane Hypothesis. Urey finally accepted this suggestion after some apparent reluctance as he was not really an experimentalist. So, together they designed an apparatus that they filled with a mixture containing the most abundant element in the Universe, hydrogen, followed by the elements carbon, nitrogen and oxygen as

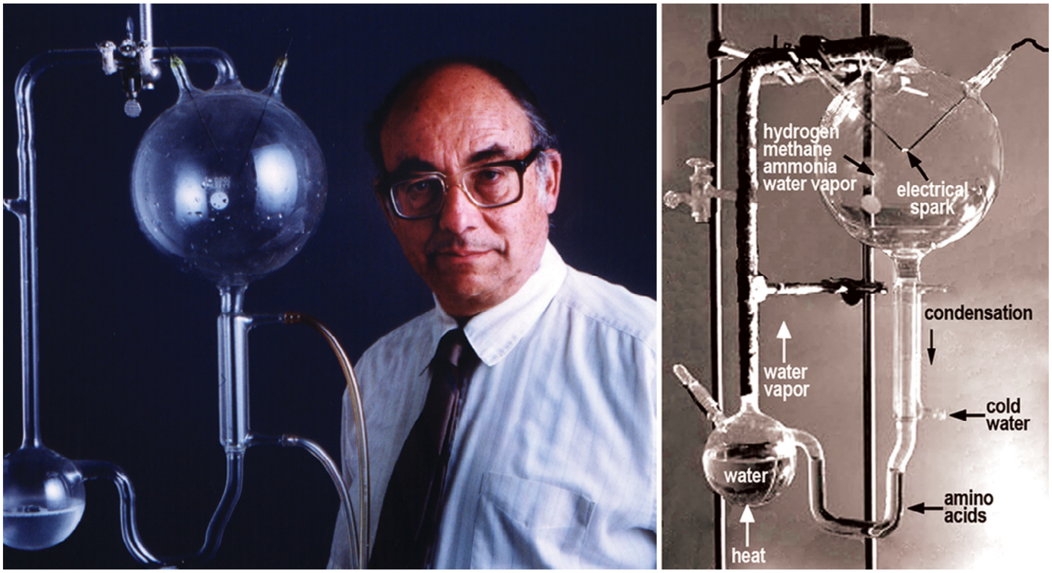


Fig. 22
Stanley Miller and the apparatus he used in his experiment.
Credit: NASA.
URL: http://commons.wikimedia.org/wiki/File:SLMILLER.JPG

their hydrogenated derivatives (hydrides), namely, methane, ammonia and water (Fig. 22). This gaseous mixture was subjected to high voltage electric discharges, in an attempt to reproduce the conditions that were thought to mimic the primitive atmosphere and oceans during the lightning storms that would have devastated the early planet. Shortly afterwards, amongst

4 The term "reductive" means that it is rich in hydrogen and hydrogenated compounds•

other unknown products, Miller identified four of the amino acids that are obtained by hydrolysis of proteins.[5] This result was the first experimental evidence for the hypothesis of Oparin-Haldane and was published in 1953 in Science, the highly credited journal, but only under the student's name. It has never been convincingly explained why the supervisor did not want to endorse the work, but the truth is that these results caused a sensation around the world. In the middle of the last century it was still a matter of controversy in some scientific circles as to whether proteins or nucleic acids were responsible for heredity and the key to Life. However, the publication in that same year of the molecular and structural constitution of nucleic acids[6] made it become universally accepted that the key to heredity lies in DNA molecules. Although the action of DNA is assisted by proteins, the controversy ended and the Urey-Miller experiment lost some of the significance that some had assigned to it.

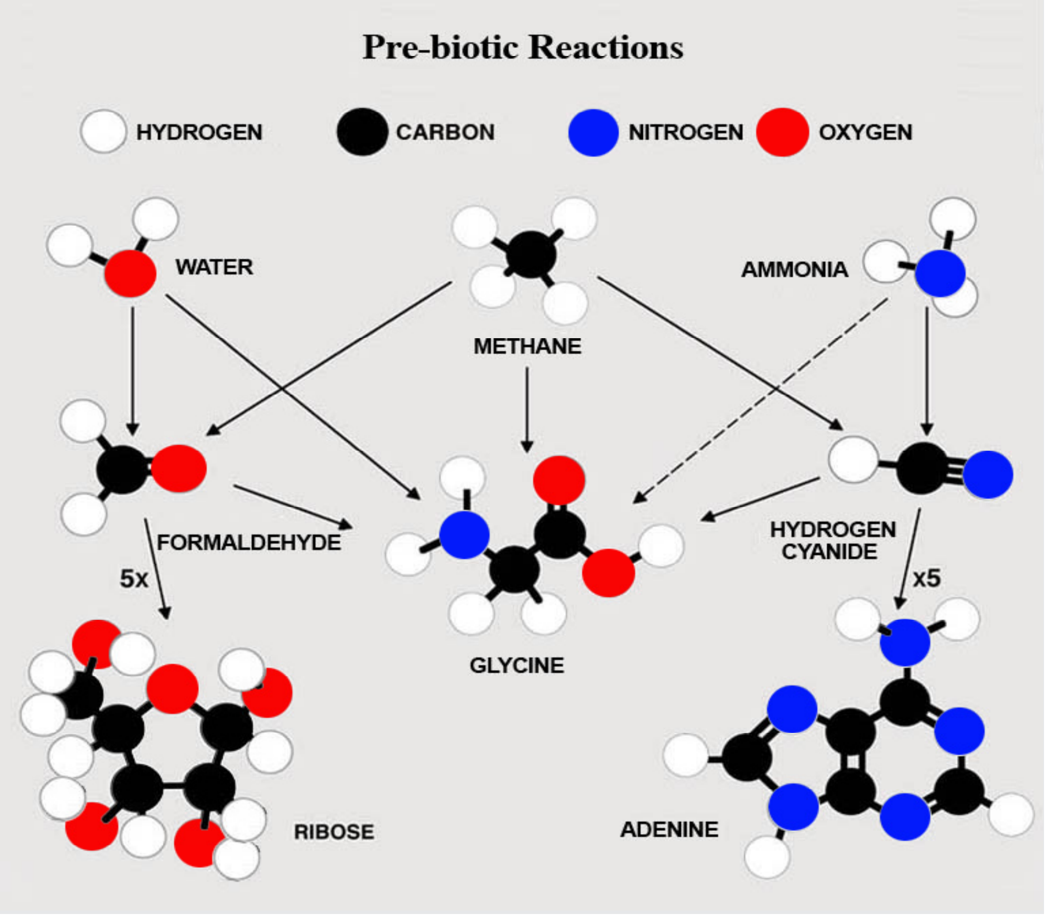
Since its first impact, the Urey-Miller experiment has received criticisms that have depreciated it, the first being on the use of an excessive amount of ammonia, since it was known

Results from Urey-Miller Experiments

	REAGENTS		Amino acids $NH_2\text{-}CHR\text{-}CO_2H$
	1st Experiment $H_2 + CH_4 + H_2O + NH_3$	2nd Experiment $H_2 + CH_4 + H_2O + N_2$ NH_3 (only traces)	R
PRODUCTS (DNA coded amino acids)	glycine	glycine	H
	alanine	alanine	CH_3
	aspartic acid	aspartic acid	CH_2CO_2H
	glutamic acid	glutamic acid	$CH_2CH_2CO_2H$
		valine	$CH(CH_3)_2$
		leucine	$CH_2CH(CH_3)_2$
		serine	CH_2OH
		isoleucine	$CH(CH_3)CH_2CH_3$
		threonine	$CHOHCH_3$
		proline	$CH_2CH_2CH_2(N)$
		(cystine)	CH_2SH

that sunlight rapidly decomposes ammonia into nitrogen, which is the main component of the Earth's present atmosphere; also hydrogen, because it is the lightest of gases, rises rapidly in the

5 Proteins have many functions in living organisms, usually in conjunction with messages originating in DNA. By hydrolysis, i.e. by treatment with water under certain conditions, they break down into amino acids.
6 DNA and RNA are nucleic acids.



atmosphere and is lost in outer space.[7] The experiment was therefore repeated with a mixture containing only traces of ammonia; of the numerous amino acids identified in the product, ten (instead of the initial four) were identified out of the twenty that may be obtained by hydrolysis of proteins.[8] If in the experiment the hydride of sulfur (hydrogen sulfide, H_2S), is also used, one further amino acid is obtained. Whilst investigating his experiment in detail, Miller came to the conclusion that the reaction initially produced aldehydes and hydrogen cyanide. Once formed, the aldehydes react spontaneously with the hydrogen cyanide and some ammonia; subsequently, the amino acids are formed by the action of water. From the chemical point of view, the novelty of this reaction was the production of aldehydes and cyanide, as the forma-

7 Today 10^7 hydrogen atoms per square centimeter are lost on our planet every second.

8 The amino acids obtained by hydrolysis of proteins are commonly known as "DNA-coded amino acids", since in DNA one or more codons exist for each of these compounds. These codons ensure the synthesis of proteins within living cells, each codon consisting of a sequence of three nucleotides. The DNA consists of an alternating sequence of phosphate and sugar linked together; one of the four nucleic bases is also bound to each sugar unit. Each set of phosphate, sugar and nucleic base is called nucleotide.

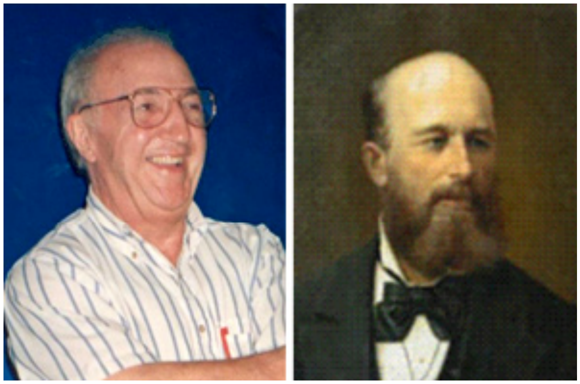


Fig. 23
Joan Oró and Alexandr Butlerov.
Oró's photo by courtesy of Agrupación Astronómica de Castelldefels, Barcelona, Spain.

tion of amino acids at the expense of these materials had been known since the mid-nineteenth century, as described by Adolph Strecker (*cf*. Chapt. 2) in 1850. It is quite significant that, of the compounds formed from the three chemical elements C, H, and N, hydrogen cyanide and formaldehyde[9] are amongst the most abundant in the Universe.

This experiment received further criticism, relating to the fact that it was carried out in a closed system. Since the reactions involved in the formation of aldehydes and hydrogen cyanide release hydrogen, in a closed system the pressure of this gas increases during the process; this is in total contrast with the open system of the Earth, where the hydrogen pressure has always been low because of its constant depletion.

The living organisms that presently exist on Earth are based on DNA and/or RNA, species that contain genetic information that is passed on to descendants. DNA and RNA are macromolecules formed by nucleotide sequences; hydrolysis of nucleotides leads to phosphoric acid, a sugar, and one of the following nucleic acid bases, adenine, guanine, thymine and cytosine or uracil. In 1960, Joan Oró (1923–2004) discovered that, by heating an aqueous solution of hydrogen cyanide and ammonia, adenine and guanine are obtained. In 1968, by condensation of cyanoacetylene with urea, Leslie Eleazor Orgel (1927–2007) and his colleagues synthesized the remaining nucleic bases, *viz*. cytosine, thymine and uracil. Both cyanoacetylene and urea are prebiotic compounds, that can be obtained in experiments similar to that of Miller and are found in outer space.

By treatment of an aqueous solution of formaldehyde with calcium hydroxide, or an equivalent catalyst, one obtains a mixture of various sugars. This reaction was first described in 1861, by Aleksandr Butlerov (1828–1886), with ribose and glucose being among the sugars obtained. Ribose is the sugar that exists in the nucleotides of RNA,[10] while glucose is abundant

9 The molecule of hydrogen cyanide is formed by a hydrogen, a carbon and a nitrogen atom; the molecule formaldehyde consists of two atoms of hydrogen, one of carbon and one of oxygen.
10 RNA are the initials of the words RiboNucleic Acid, where "ribo" refers to ribose.

in Nature and can be obtained, for example, by total hydrolysis of cellulose. The syntheses described above, performed with prebiotic reagents, are important steps in the search for clues to the origin of Life; nevertheless, it has not yet been possible to explain the formation of nucleic acids in the primitive Earth's environment.

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4.3 Polymerization experiments

GIVEN THAT THE SYNTHESIS OF SIMPLE ORGANIC compounds would be possible from the reagents existing in the prebiotic Earth, the question then arises as to whether it would have been possible, and by what mechanism, such compounds could be transformed into proteins, nucleic acids, lipids and polysaccharides, molecules essential to Life as we know it. In 1956, Sidney W. Fox (1912–1998) discovered that by heating mixtures of amino acids rich in aspartic acid and/or glutamic acid to 180 ºC, microscopic globules were formed, that possessed a double membrane that, by selective permeability, not only enabled them to grow by absorption of the medium material, but allowed them to divide spontaneously into two identical particles as they reached a certain critical size (Fig. 24). Later, the author obtained similar results at lower temperatures, when salt from seawater was added to catalyze the reaction. Initially these globules were known as microspheres, but eventually Fox called them, wrongly and improperly, proteinoids, protocells and even protobionts. They are indeed polymers of amino acids like proteins, but their structure is very different. At present it is unknown whether these microspheres had any involvement in the processes that led to Life.

Although transmission of information between generations is ensured by DNA, this is a molecule that does not promote any action directly on its own; it contains the genetic information that is the key to Life, but is unable to do anything with it without the contribution of proteins.

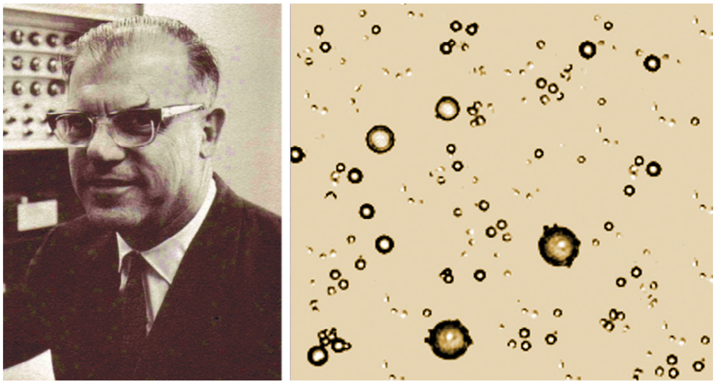


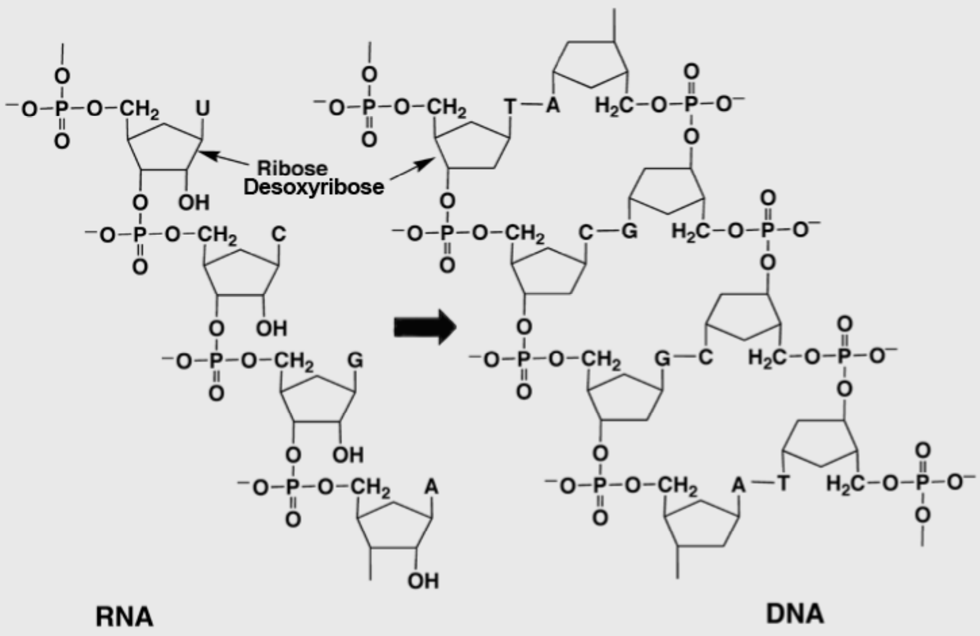
Fig. 24
Sidney W. Fox and his "microspheres".

In turn, proteins are able to promote thousands of reactions as catalysts and, in a very primitive way, to encode structural information contained in the way amino acids are organized in their molecules; however, they seem unable to reproduce this information directly. This gave rise to an issue that has stood for decades, *viz*. what came first, DNA, which only contains the information or the proteins, which are responsible for the biochemical changes but cannot reproduce themselves? This fundamental question leads us to a new hypothesis, with which we deal below.

4.4 The RNA World hypothesis

THE TERM "RIBOZYME" APPEARED FOR THE first time in 1982 in an article published in the journal Cell to designate small molecules of RNA, with the aim to demonstrate their catalytic properties by analogy with the word "enzyme". Four years later, in 1986, based on the knowledge that RNA can catalyze chemical reactions in a manner somewhat similar to the way proteins behave when acting as enzymes, Walter Gilbert (1932–),

Structure of ribonucleic (RNA) and deoxyribonucleic (DNA) acids



A = Adenine, G = Guanine, C = Cytosine, T = Timine, U = Uracil

Nobel Prize in Chemistry in 1980, proposed the expression "RNA World" to designate a hypothetical stage of the process that would have established Life on Earth. DNA, the genetic material of most existing living beings, not only ensures the codification of the information connected with heredity but also the information that allows regulation of the normal functioning of all constituent parts of such beings, including the construction of the protein molecules of each individual. However, while ribose, the sugar that is part of the RNA molecule, is clearly the product of incorporation of five molecules of formaldehyde in a single molecule of sugar, the same cannot be said with respect to DNA. The sugar involved in the constitution of this genetic material is deoxyribose, that cannot be produced directly from formaldehyde; the molecule of deoxyribose differs from that of ribose by having one atom of oxygen fewer. Thus, while RNA is very probably a direct derivative of the abundant prebiotic formaldehyde, DNA appears to be a product of a seemingly accidental chemical change of RNA (or ribonucleotides), i.e. a product of a chemical evolutionary mutation of RNA. This seemingly small difference is enough to make DNA more stable than RNA; while the latter has as many OH groups in its molecule as the number of its nucleotides,[11] the former contains none; the OH groups are chemically very reactive, making RNA a "short lived" species that decomposes rather quickly in reaction with its solvent medium. This difference may have opened the way for DNA to dictate the course of evolution in a genuine process of natural selection.

Therefore, the "RNA World" hypothesis considers that rather than involving DNA, the original genetic material may have comprised small molecules of RNA, namely ribozymes, which would have developed a simple self-reproductive system. Such a system would combine two roles, i.e. to include genetic functions for transmission of information and to operate as enzymes. Subsequently, proteins would have arisen, assuming the catalytic role of RNA and its evolution to more complex structures. DNA would have arisen later, replacing selectively and naturally the role of RNA in recording and transmitting information, thanks to its greater stability. All evolutionary processes — mutations, recombinations and duplications — would then follow, leading to the formation of more complex organisms. However, the lack of knowledge as to how the first RNA molecules emerged in a prebiotic Earth, to be followed by DNA, is still a major problem

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11 An OH group (formed by one atom of oxygen and one of hydrogen) is typical of alcohols; the larger the percentage of OH groups is in a molecule, the more soluble the compound in water.

Chapter 5

Exogenous origin of Life — Panspermia

Let us rise above this sad Earth and see from above if nature has exhausted all its wealth and beauty in this little piece of dust. Thus, as those who travelled to distant countries, we can better assess what was done with us and give each thing its fair value. We will turn our admiring less to what in this world is considered great and will even despise those trifles to which the majority of men tie themselves, when we realize that there is a large number of inhabited Earths as ours and as beautiful as ours.[1]

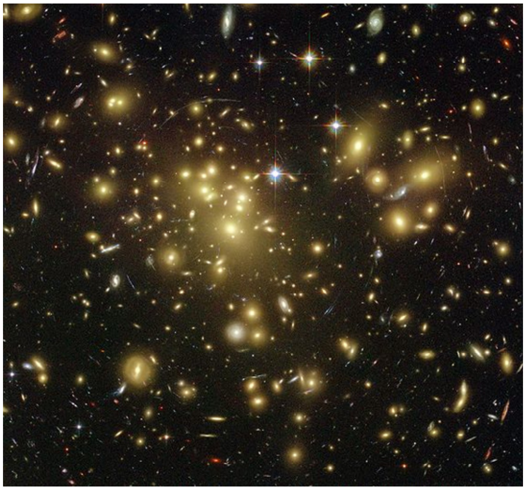

Fig. 25
Deep space as seen by the Hubble Space Telescope.
Credit: NASA, N. Benitez (JHU), T. Broadhurst (Racah Institute of Physics/The Hebrew University), H. Ford (JHU), M. Clampin (STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA.
URL: http://www.utahskies.org/HST/Archives/galaxies.html

THE HUMAN MIND HAS BEEN ENDLESSLY fascinated by the possibility of Life existing outside the Earth. The oldest records relating to this issue date from the seventh century BC and are due to Anaximander (c. 610–c. 540 BC). Several authors have taken up this idea since the Renaissance, but only from the mid-nineteenth century and, especially, throughout the second half of the last century, has scientific progress led to the possible assumption that Life may not be an exclusive of our planet.

The hypothesis that attempts to explain the emergence of Life on Earth on the basis of its having been transported from another place in the Universe is called Panspermia (from the

1 Christiaan Huygens (1629–1695), "The Celestial Worlds Discovered", 1690.

Greek *pan*, total, and *sperma*, seed). This is a deep-rooted idea that has had notable defenders over time. Anaxagoras (500–428 BC) had already spoken of the "seed of Life" from which all organisms might derive. However, the first proposals concerning Panspermia that were supported by scientific data are due to the Swedish chemist Jöns Berzelius (1779–1848), to the German physician Hermann Richter and to the physicists William Thomson (Lord Kelvin) (1824–1907), in England, and Hermann von Helmholtz (1821–1894), in Germany. Panspermia reached the level of a detailed and widely discussed hypothesis through the efforts of the Swedish chemist Svante Arrhenius (1859–1927), Nobel Prize in Chemistry in 1903, who most popularized this theory. Later, the same idea was taken up by Leslie Orgel and Francis Crick (1916–2004) and, more recently, by the English astronomer Fred Hoyle (1915–2001) and his co-worker and follower, the Sri Lankan astrophysicist Chandra Wickramasinghe (1939–).

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5.1 Lithopanspermia

On March 6, 1809 a meteorite fell on the outskirts of Alais, in southern France (Fig. 26). Much later this meteorite, together with other alien materials (siderolites), happened to be examined by Berzelius. In 1833 this scientist issued a report in which he especially publicized the object that had fallen in Alais, because he had found it contained "carbonaceous material" similar to terrestrial humus, that in his view was not from this planet. Years later, other meteorites have been identified with characteristics similar to the Alais

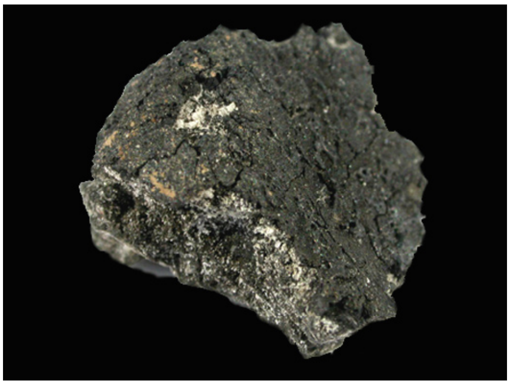

Fig. 26
The meteorite of Orgueil, fallen in France in 1864.
Courtesy of Peter Marmet, Switzerland.
URL: http://www.marmet-meteorites.com/id34.html

meteorite, which geologists now call "carbonaceous chondrites", examples being found on October 13, 1838, near the mountains of Cold Bokkveld in Cape province (South Africa),

on April 15, 1857, in Kaba, Hungary, and on May 14, 1864, in the village of Orgueil, in the southwest of France (Fig. 26). The last named differed from the others in having a high amount of carbon, which led to its being examined by Pasteur and Marcellin Berthelot (1827–1907) in France, and by Wöhler in Germany. All concluded that, amongst other materials, the rock contained organic matter, although the existing analytical methods did not provide more detailed information; however, there remained the idea that these materials might be connected with the existence of extraterrestrial Life. Believing that Life was eternal, Lord Kelvin, ignoring Darwin's theory of evolution because he believed that it was in disagreement with the "Second Law of Thermodynamics" which he had formulated for the first time, supported these ideas that Life would have been sown on Earth by meteorites, "ruins of another world". This theory became known as Lithopanspermia.

5.2 Radiopanspermia

DISCUSSIONS ON THE QUESTION OF THE existence of Life beyond our planet have been and continue to be frequent. One of the planets that has always stood out as the focus of such debates is Mars, and indeed many believed it was or had been inhabited by intelligent creatures. At the beginning of the twentieth century, when the idea of intelligent Martians began to fall into disrepute, the concept of cosmic panspermia appeared to admit the existence of Life throughout the whole Universe, and that different planets would be

Fig. 27
From left to right: Jöns Berzelius, William Thomson (Lord Kelvin) and Svante Arrhenius.

"seeded" by microorganisms called "pansperms" or "cosmozoas" (proposed by Arrhenius in 1908) or by "biogenes" proposed by Julius Schultz (1862–1936) in 1929.

Arrhenius admitted that the pressure exerted by sunlight would be capable of impelling particles with dimensions equal to or less than a micrometer (10^{-4} cm). By panspermism, microorganisms existing free in space could contaminate any planet bearing conditions favorable to Life. In this way they would have reached the Earth, driven by radiation pressure or transported through space by meteors, so becoming the first forms of Life on our planet. Arrhenius's ideas led to a variety of experiments such as those of Paul Becquerel (1879–1955), to test whether the spores and bacteria could survive in circumstances that were thought to be close to those of outer space. Most scientists came to the conclusion that probably the UV radiation would be lethal for all bodies in the interplanetary medium, ignoring all other adverse conditions these spores might experience before reaching Earth. Mainly for this reason, the ideas fell into disrepute and were only revived four decades later. Another factor that has weakened the theory was that if the Earth had been "invaded" by spores from space, at no point did it answer the inevitable question: —Where did they come from and how were such spores produced? Although this theory leaves many open questions and does not explain the origin of Life, it makes important predictions about how some form of Life could exist on different planets.

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5.3 Directed Panspermia

By mid 1970, Orgel and Crick revived the concept of panspermia by proposing that Life might have arisen on Earth by means of spores carried by a spacecraft, this vehicle having been sent by intelligent aliens to colonize our planet and probably other planets! Life on Earth would then have arisen from the multiplication of spores in the primitive ocean. One argument in favor of this theory was the fact that molybdenum, a rare element on this planet, is essential for the functioning of many enzymes that are vital to the metabolism of living beings and, thus, the probability of such enzymes and Life being originally generated in this planet would be very low. Another argument relates to transportation; a spacecraft would protect the precursors of Life on Earth from the hostile conditions they would experience if they traveled to our planet directly. This idea was the subject of many discussions and had a great impact amongst lovers of science fiction, at a time when there was much talk of UFOs and aliens, perhaps associated with rumors related to the "cold war" between the Americans and the Soviets. However, this was simply speculation, because neither was there nor is there any evidence for the existence of intelligent beings outside the Earth.

5.4 Ballistic Panspermia

Although Arrhenius' ideas had no scientific support, he later found supporters in the guises of Hoyle and Wickramasinghe. Hoyle argued that "spores of Life" are part of interstellar clouds, and comets would be the reservoirs of these spores, carrying them to planets when collisions occur. Original microorganisms would have reached Earth via comets, that would have arrived about 4 Gyr ago. This hypothesis directly challenges the idea of the origin of terrestrial life from a "primordial soup". Hoyle speculated wrongly that the number of possible combinations between the amino acids found in proteins is so

Fig. 28
From left to right: Leslie Orgel, Francis Crick and Fred Hoyle

large that the probability of a single protein arising in a significant amount from Oparin's "primordial soup" would be virtually nil, even on the cosmic scale; that would be so if these combinations were all equally probable, but that is not the case. Moreover, the comet, he argued, is a wonderful interstellar vehicle whose tail liberates enough heat to protect its eventual micro-passengers from the extremely low temperatures of space. Following alleged collisions with Earth, such organisms would have found an environment that would allow them to have nourishment and favorable conditions for development. Hoyle and Wickramasinghe have even stated that many of the pests and epidemics in the history of humanity were caused by viruses brought by comets, but this idea has never found any acceptance within the scientific community.

In order to produce an acceptable scientific basis any theory must, at least in principle, be verifiable experimentally. Hoyle and Wickramasinghe sought to identify the components present in interstellar dust, by means of "traces" of infrared radiation (IR) emitted by the dust, or by the absorption of visible light that passed through the clouds. From analyses they carried out in the 1970s, they claimed to have found evidence of the pres-

ence of complex "polymers" in space, especially molecules of "polyformaldehydes". This led them to believe that a substantial fraction of interstellar dust would consist of organic polymers. But their analyses were erroneous, one particularly serious one being when they announced that they had found sugars in outer space, when they had actually found evidence of water. Along with methane and possibly ammonia, water is undoubtedly one of the most abundant compounds in the Universe, but until recently these astronomers tended to deny its existence in places other than Earth

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5.5 Panspermia under a new perspective

As techniques in chemical analysis have been gradually improved, especially with respect to the most modern and sophisticated mass spectrometers, new meteorites have been studied and old ones reanalyzed. Amongst them are those of Orgueil (1864), of Murray in the U.S. (1950), of Murchison in Australia and of Allende in Mexico (both 1969). In these objects many amino acids were initially discovered (and today more than seventy different species are cataloged) but later other compounds such as nucleic bases and substances related to sugars have also been found. These findings altered significantly the concepts held on the abiotic synthesis of organic compounds on our planet. Recalling what was said above with regard to the Urey-Miller experiment, it became clear that the physical and chemical conditions they considered to simulate the Earth's primitive environment should certainly have been, and still are, satisfied in other parts of our solar system in particular, and of the Universe in general. This original experiment thus represents today a much more general and universal scenario than originally thought.

Indeed, during the last two decades it has become increasingly clear that the chemical elements generated from particles of matter emitted by stars form the basis of many compounds that are indispensable to the production of the so-called "monomers of Life". When these are produced in suitable environments or are transported to such environments, such compounds change into these monomers. The carbonaceous chondrites, which are among the most primitive meteorites,[2] may contain up to 10% of organic matter. Over long periods of time these bodies should have brought to Earth enormous amounts of chemical materials produced elsewhere in our solar system, or even outside it, thus sowing the planet with amino acids, nucleic bases and perhaps sugars, compounds that are essential to Life just as we know it. It is then presumed that chemical evolution, that began outside our planet, has been continued until the first living being was generated. By comparison with the concept of panspermia,

2 As in the case of terrestrial rocks. meteorites are classified on the bases of their composition and texture; they are divided into three main groups, *viz*. metallic or ferric, petro-ferric and stony. The oldest meteorites are stony, and among these, the oldest are chondrites. The latter are amongst the first matter to solidify from the cloud of gas and dust that gave rise to the Solar System. Carbonaceous chondrites are particularly important because they contain appreciable amounts of extraterrestrial organic compounds.

there is now place for a new concept, that of "chemical panspermia", associated with a universal chemical evolution and based on the chemical constitution of meteorites. However, to date there is no evidence to confirm definitively that these bodies contain matter associated with living beings. Indeed, the organic matter existing in them must have been formed under abiotic conditions, by chemical reactions occurring within the pre-solar nebula, chemical reactions that we can reproduce in the laboratory. However, one continues without knowing — it cannot be repeated too often — how such monomers have evolved to generate the complex compounds and chemical mechanisms that we know in living beings.

In spite of what has just been stated, the meteorite named ALH 84001, found in Antarctica and recognized as originating from Mars, shows sign that some scientists admit to being fossils of unicellular living creatures (Fig. 29). From its dating, it is concluded that its age is 4.5 Gyr, that it was ejected from the red planet about 17 million years ago and that it fell to Earth about 13,000 years ago. Inside it, within tiny slits, some shapes have been found that many believe may be of ancient bacteria. There are four main pieces of evidence leading to this conclusion. The first is that the meteorite has certain Martian origin and contains carbonate globules. The second is the presence of complex organic molecules known as polycyclic aromatic compounds. The third is the presence of iron and compounds similar to those that can be produced by bacteria. The last, and perhaps the most intriguing piece of evidence is that what is observed seems clearly to be fossilized bacteria. The observations of the Nakhla (Egypt, 1911) and the Shergotty (India, 1865) meteorites, also originating in the red planet, are equally surprising. Ten years ago, Richard B. Hoover, from the Marshall Space Flight Center (NASA), found some shapes in the Murchison meteorite suggesting they are fossils of microorganisms. Similar observations were also recorded with regard to the Allende meteorite. Neither of

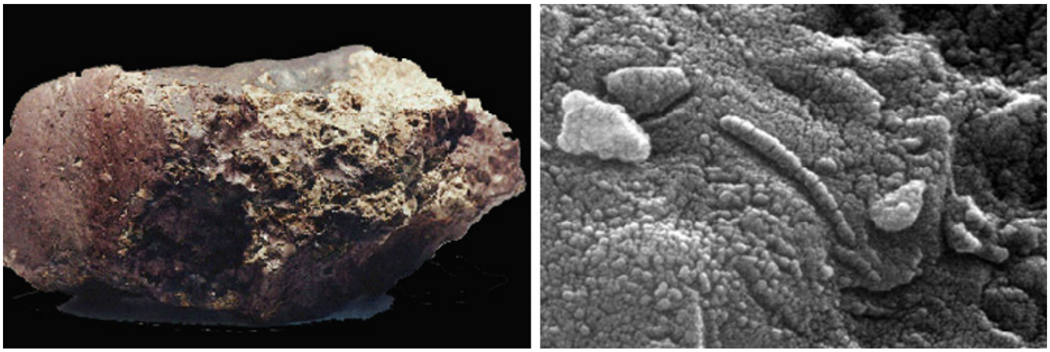

Fig. 29
The ALH 84001 meteorite and some microscopic shapes found in it.
Credit: JSC, NASA.
URL: http://en.wikipedia.org/wiki/Allan_Hills_84001

these meteorites came from Mars, but their structures are significant, and may add further weight to the concept of chemical panspermia.

In a relatively recent past it was argued that the inhospitable environment of the interplanetary and interstellar media would not allow the transport of Life through such media. However, recent discoveries to be discussed in the next chapter, have shown that certain forms of Life (extremophiles) can proliferate in environments that until recently were considered totally adverse, perhaps as adverse as those of meteorites, comets, or of other small sized celestial bodies travelling throughout space. These discoveries have provided new strength to the above ideas. The search for Life in places where in the past no one has searched has now gained ground and higher credibility.

Thus we have virtually travelled full circle being almost back with Lord Kelvin's Lithopanspermia! Discussions continue within the scientific community as to whether meteorites or comets are sowers of spores through space. But the search as to how the first living being was generated, and whether it was on Earth or in any other part of the Universe, still remains unanswered.

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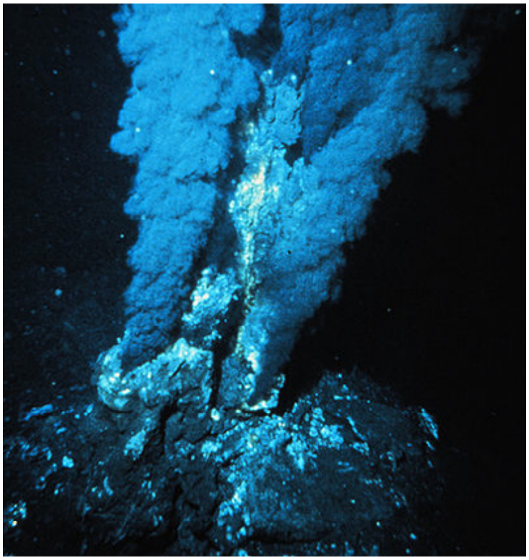
Chapter 6

Life as we did *not* know it



In Nature the role of the infinitely small is infinitely large.[1]

Fig. 30
A submarine hydrothermal chimney in the Atlantic ridge, a habitat for extremophile flora and fauna.
Credit: US NOAA.
URL: http://en.wikipedia.org/wiki/File:Nur04506.jpg

OVER TIME, A COUNTLESS NUMBER OF beautiful and fascinating forms of Life, has evolved and continues to evolve on our planet. Many of them are very familiar to us, but others are not, escaping the traditional idea we have of Life. The truth is that microorganisms are able to proliferate in a variety of environments characterized by extreme temperatures, salinity or acidity values, which at first sight would prevent any form of Life — the so-called extremophiles.

This term was first used in 1974 by R.D. MacElroy, to designate microorganisms that proliferate in "extreme and inhospitable environments". But what are "extreme and inhospitable environments"? Its definition can be understood with two different meanings.

1 Louis Pasteur (1882–1895).

Taxonomists define them as those environments that have a limited biological diversity, since most of these organisms are excluded. Moreover, the anthropomorphic definition considers as “mild” the environments that have temperatures up to 40 °C, acidity values close to neutrality, salinity similar to that of the oceans, atmospheric pressure and radiation levels similar to those that are typical of the Earth’s surface. So, in light of the latter definition, extreme and inhospitable would be those environments that are lethal to most living beings, such as the polar regions, hydrothermal vents, acidic or alkaline springs, lakes with high levels of salinity, cold abyssal regions or areas covered with high levels of radiation.

In reality, until very recently it was assumed that Life could only exist in conditions similar to those to which we are accustomed. At present, it is known that the thermal and environmental limits of living forms extend along much broader values, many microorganisms being able to bear temperatures well below 0 ºC and some bacteria able to reproduce easily above the boiling point of water. It is also amazing that Life is possible in extremely acidic or alkaline media, or in saturated solutions of sodium chloride, for example. In fact, apparently inhospitable habitats harbor microorganisms that seem suited to the aggressiveness of these environments, since it is there that they live, develop and multiply.

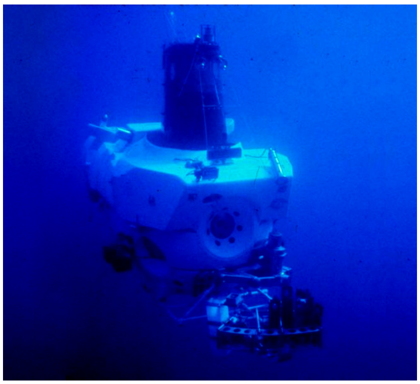


Fig. 31
The submersible “Alvin”, from the National Oceanic and Atmospheric Administration (NOAA, USA), used in expeditions to the bottom of the oceans, including one that in 1977 discovered extremophiles near submarine hydrothermal vents off the Galapagos Islands.
Credit: NOAA’s Undersea Research Program and Rod Catanach, Woods Hole Oceanographic Institution.
URL: http://www.nurp.noaa.gov/Spotlight/OceanDumping.htm

In 1977, in an expedition of the National Oceanic and Atmospheric Administration (NOAA, USA), aboard the submersible “Alvin” (Fig. 31), to the depths of the Pacific Ocean, about 500 kilometers northeast of the Galapagos Islands, the unexpected was found. At a depth of approximately 2,500 meters, many living species proliferated around hydrothermal chimneys, from blind shrimp and other strange forms of Life to bacteria, all

perfectly adapted to a medium subjected to a pressure of 40 kilograms per square inch and temperatures above 100 ºC. They were extremophile beings, never seen or guessed before; their habitat was extreme not only with regard to pressure and temperature, but also to the environment being extremely polluted by gases, with plenty of sulfur compounds and other materials lethal to common living beings, expelled from the interior of the planet through chimneys in the ocean bottom. This discovery has changed forever our way of seeing our planet and its life therein, bringing up many questions and raising the scientific curiosity for all kinds of possible habitats hitherto considered unsuitable for Life. In particular, it has reawakened the possibility of Life existing or having existed in other places of the Universe up to then considered inappropriate; this led NASA to become interested in this matter and quickly invest in a considerable number of missions with the purpose of carrying out new explorations.

Hydrothermal springs are formed by chimneys situated in places where different tectonic plates join and where water circulates. The ocean bottom has numerous cracks through which water comes into contact with hot rocks, recently formed from magmas. The rocks at higher temperature can be found mainly along the oceanic rifts,[2] which are underwater mountain ranges where rocks rise continuously from the bottom of the sea. The water infiltrates through these cracks and reaches very high temperatures. When heated, it rises and drags various metals from the surrounding rocks, thus forming water springs. When it emerges from the ocean floor, this fluid is rich in metals and deposits solid waste around the opening, which generates a real chimney. This chimney smokes continuously at temperatures that reach 360 ºC, and remains active for decades, creating conditions for the development of a strange ecosystem. Biomass estimates were found to be 10^4 to 10^5 times larger than those of other populations existing at the same depth. It is an authentic oasis of Life, Life that is very different from what was thought to be possible.

In the deep hydrothermal regions nearly 400 unknown species were discovered. At such base of the food chain there are bacteria that get their vital energy from oxidation of sulfides present in fluids that emerge from the underwater chimneys. Worms and huge bivalve molluscs up to 26 centimeters in length are found, which feed on these bacteria. Strange species of crabs and shrimps and other more complex animals appear at the end of the food chain. A curious fact is that most species existing there only survive in these environments, which raises many still unanswered questions. How did Life appear in these places, at first sight so inhospitable?

Other underwater regions that are now the target for large investment and study are the areas of cold exudations. In these areas, where worms were found in 1997, methane builds up under the form of hydrates. Already in 1984, the geologist Charles

2 Rifts are regions where the Earth's crust and its associated lithosphere are undergoing a fracture accompanied by a separation in opposite directions.

Paull, of the Monterey Bay Aquarium Research Institute (USA), discovered another kind of environment in the oceanic bottoms of California, able to provide nutrients for a chemosynthetic life. These environments are sources of methane, in which cold fluids with high concentrations of methane and sulfides are released through sediment layers on the bottom of the oceans. The sources of methane occur in active and passive margins of continents, at depths between 400 and 8,000 meters. As in the hydrothermal springs, the biological communities of the methane springs are supported by chemosynthetic bacteria, i.e. bacteria that use chemical energy instead of the solar energy required by photosynthetic beings. These bacteria are found in their free form and in symbiotic associations with invertebrates such as tube worms, mussels and clams.

The search for Life in places where in the past nobody would have thought worthwhile now gained meaning and greater credibility and, more than this, many laboratories and companies became interested in developing research programs in this field. Indeed, the knowledge of the metabolic mechanisms and chemical materials that allow extremophile beings to resist the adverse conditions in which they proliferate opens numerous routes with high economic value in the field of medical biotechnology, food biotechnology and other areas of the economic activity. At the same time, the results of studies conducted under these programs will be providing valuable information about the origin of Life on Earth, and their adaptive strategies to environments where it prospered, since the ability to adapt to environmental change is one of the most impressive features of Life on our planet. And much information has already been obtained during the last thirty years.

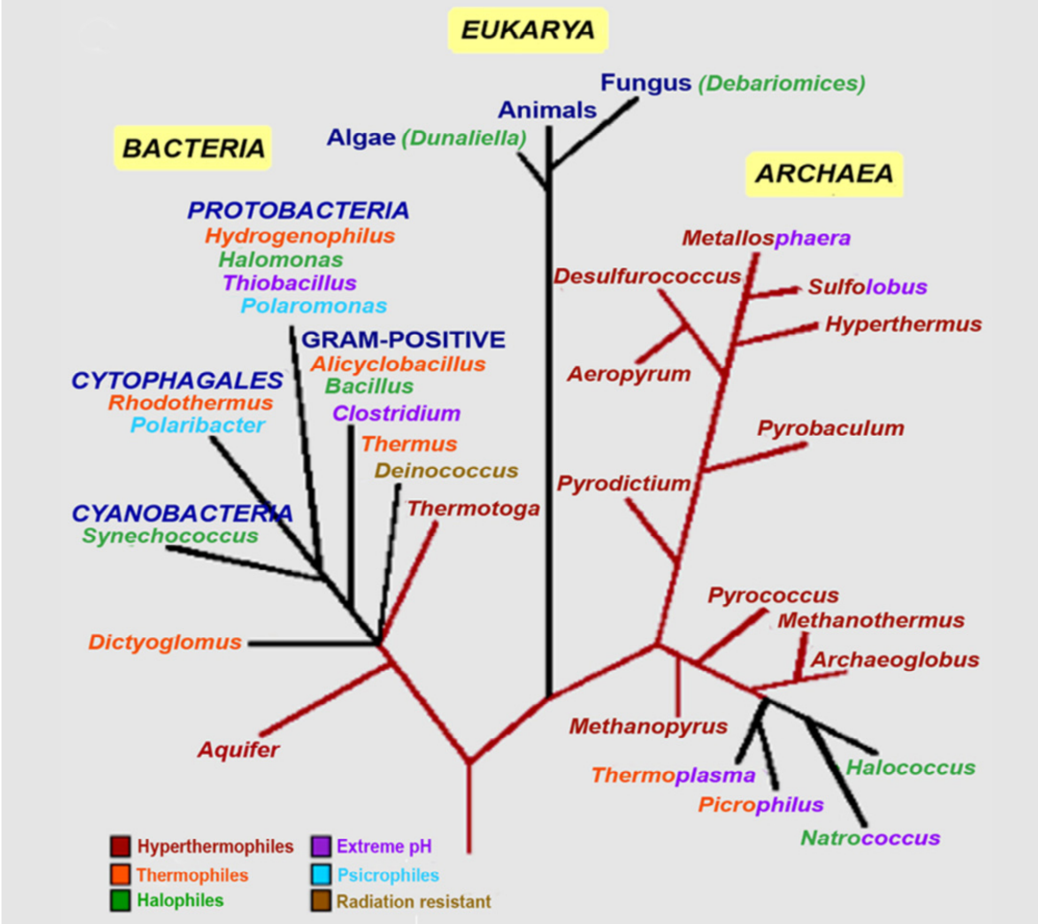
Until recently it was believed that Life on Earth was possible only when the environment had become favorable for it to occur, with an appropriate temperature and atmosphere. Then, primitive beings would have started to proliferate, such as lichen or algae, and later, when the circumstances allowed it, bacteria appeared. It was accepted that the latter could only flourish within very narrow environmental limits. To the surprise of the scientific community, in recent years and after the discoveries made in submarine hydrothermal sources, bacteria were found to grow and live in other habitats with extremely difficult conditions and in the most unlikely places of the planet. It is surprising that many of these microorganisms grow better in environments that to our eyes are inhospitable, than in the so-called "natural environments". More than this, they require this hostility to be able to reproduce.

In the following paragraphs we shall take you on a "trip" within the fascinating world of extremophiles, exploring briefly their diversity, physiology, strategies they use to survive and, finally, the great importance of their study in the context of the origin of Life.

6.1 Extremophiles

UNTIL THE TWENTIETH CENTURY LIVING beings were classified into two kingdoms, the animals (fauna) and plants (flora). However, as new forms of Life were discovered, mostly in the microscopic world, and knowledge of Life on Earth increased, the former classification proved unable to cope with its diversity and complexity. So, between the mid-1950s and the mid-1960s, the whole living world was organized into five kingdoms, *Monera, Plantae, Animalia, Protista* and *Fungi* separated into two main categories, the

Phylogenetic tree according to C. Woese, with lists of extremophiles



Translated from Helena Santos, Pedro Lamosa and Milton S. Costa
URL: http://dequimica.ist.utl.pt./bbio/69/pdf/extremofilos.pdf

Extremophiles

Environment parameter	Name	Caracteristics
Temperature	Hyperthermophile Thermophile Mesophile Psychrophile	Grows at 80-115 ºC Grows at 60-80 ºC Grows at 15-60 ºC Grows below 15 ºC
Radiation	Radiophile	Tolerates UV and gama radiation
Pressure	Barophile Piezophile	Weight loving Pressure loving
Gravity		Grows at more than 1 G [1] Grows at less than 1 G
Vacuum		Tolerates sideral vacuum
Desiccation	Xerophile	Grows in anhydrous medium
Salinity	Halophile	Salt loving (NaCl 2-5 M)
Acidity (pH)	Acidophile Alkalophile	Grows at pH lower than 5 Grows at pH higher than 9
Oxygen	Anaerobe Microaerophile Aerobe	Cannot tolerate oxygen Tolerates some oxygen Requires oxygen
Chemical medium	Autotrophic Metanogenic Metal tolerant	Lives from pure CO_2 *Idem* Can tolerate high concentrations of metal
Physical medium	Endolith Hypolith Oligotrophic	Grows inside rocks *Idem*, in cold deserts Grows in low nutrition environment

[1] The gravitational unit is represented by "G", which is the acceleration of gravity on Earth and has a value of 9.8 meters per square second ($m\ s^{-2}$).

Eukaryotes and the Prokaryotes. The Eukaryotes included four of the five kingdoms, *viz*. *Plantae, Animalia, Protista* and *Fungi*.

However, this classification did not last long; new data from Molecular Biology have created the need for change. In fact, in the 1970s, when the American biologist Carl Woese (1928–) and his team used DNA sequences in the study of relationships between prokaryotes, they discovered that a certain type of prokaryotic organism, which long had been classified as bacteria, possessed a DNA very different from that of bacteria. This difference led to the conclusion that there are two completely different groups of prokaryotes and Woese proposed a reorganization of the Tree of Life into three distinct domains: *Eukaryota, Eubacteria* and *Archaebacteria*. The name of the latter domain was subsequently changed into *Archaea* by Woese himself. It was so designated because many believe that all living species that belong to it represent less evolved forms of Life on Earth. Their name reflects this, as the term *Archaea* means 'old'. The ability of some *Archaea* to live in environmental conditions similar to those thought to have existed in the primitive Earth provides an indication of the antiquity of this domain. Some extremophiles, especially those that proliferate in hyper-salty areas, have been known for more than six decades. However, it was the discovery, in the 1970s, of this third branch of the Tree of Life — *Archaea* — and, in the years that followed, the discovery of microorganisms proliferating at very high temperatures, near the temperature of boiling water, that brought about further discussions concerning the origin of Life. By questioning the limits of physical and chemical parameters of Life, the possibility of its existence on other planets was brought into focus.

Extremophiles are classified in accordance with the extreme environmental parameters in which they are able to thrive (*cf*. table on previous page). It should be noted that this classification is not exclusive, since many may be inserted into more than one category; for example, those living in submarine hydrothermal sources are both hyperthermophiles, barophiles, acidophiles and toxic tolerants. The extremophiles are mostly prokaryotic microorganisms, i.e. they belong to the fields *Eubacteria* and *Archaea*. So, extremophilic survival cannot be seen as a phylogenetic feature. However, the data that are available show that these microorganisms tend to belong to the domain *Archaea*. This trend is evident with regard to the organisms whose optimal growth temperature is above 100 °C; they are archaeons. With regard to those that tolerate more saline or more acidic environments, they also appear to be preferentially contained in the domain *Archaea*. Specific examples are the type *Halobacterium*, which develops in saturated saline environments (sodium chloride concentration of 5.2 moles per liter), the *Pyrolobus fumarii* (Fig. 32), which has an optimum growth temperature of 106 ºC,[3] and the type *Picrophylus* that develops at pH = 0.[4] However,

3 Proteins, such as egg white, coagulate at much lower temperature, typically above 70 ºC.

4 The pH is a measure of acidity; the pH of water is 7, that of vinegar is 4 and that of strong acids such as hydrochloric acid ranges between 0 and 1.

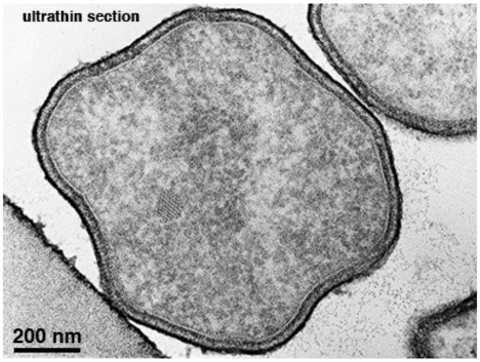


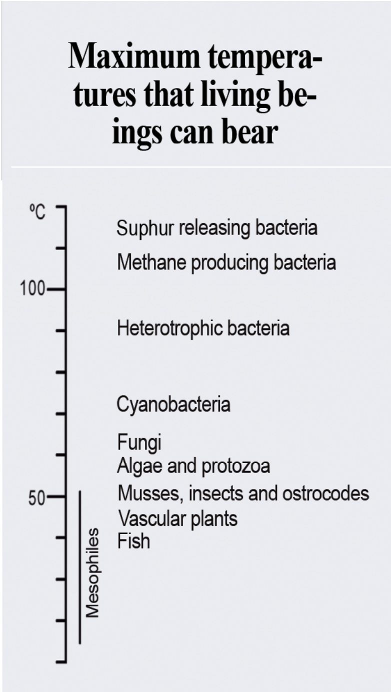
Fig. 32
Pyrolobus fumarii, a hyperthermophile living at temperatures within 90-113 ºC.
Courtesy of Professor Karl Stetter, University of Regensburg, Germany.
URL: http://www.heise.de/tp/r4/artikel/15/15412/1.html

it should be noted that, as already mentioned, the ability of organisms to resist to extreme environments is not exclusive to the domain *Archaea*. Examples are the microalgae of the type *Dunaliella* and cyanobacteria of the type *Synechococcus*, which are halophilic, and the bacteria of the genus *Thiobacillus* and *Clostridium*, which are acidophilous. Particularly notable are the microorganisms found living in nuclear waste where radiation levels are lethal to most living beings.

One must distinguish between organisms that require an extreme environment to reproduce at a normal pace and those that, while being able to withstand extreme environments, reproduce faster in less inhospitable environments. The first are the true extremophiles (*philos* = friend of), while the latter are tolerant (or resistant) to such environments. Hyperextremophiles are commonly referred to as those that inhabit environments whose physical and chemical characteristics correspond to maximum permissible limits for any known living being. To adapt to extreme environments, these microorganisms developed typical cellular structures and metabolisms.

6.2 Thermophiles and hyperthermophiles

MICROORGANISMS THAT GROW AT temperatures typically above 60 °C are considered thermophiles and those that grow at temperatures exceeding 80 ºC are known as hyperthermophiles. Both types can be found in hot and aquatic environments rich in sulfur, associated with processes of volcanism, as geysers, fumaroles, eruptive chimneys and hydrothermal springs — regions characterized by high acidity and containing iron and sulfur. However, they can also be found in hydrothermal springs with high alkalinity.



In the context of extremophilia the most surprising discovery was undoubtedly that of hyperthermophiles by Karl O. Stetter (1941–). Temperature affects the three basic types of biological molecules (lipids, proteins and nucleic acids), producing structural changes that lead, for example, to denaturation of biomolecules. Thus, when the temperature reaches 100 ºC the fluidity of their membranes breaks down; chlorophyll is degraded long before 75 ºC, thus losing its photosynthetic capacity. Consideration should also be given to the fact that the solubility of gases in water decreases when the temperature increases, so that high temperature waters are low in oxygen and carbon dioxide, gases that in many cases are essential to Life. When thermophiles and hyperthermophiles were discovered, it was a surprise to find them not only able to survive but also able to multiply at temperatures close or equivalent to boiling water — currently, the maximum temperature known at which they are known to survive is 115 ºC.

Thermophiles exist amongst phototrophic[5] bacteria (cyanobacteria, green bacteria and purple bacteria) and eubacteria (*Bacillus, Clostridium, Thiobacillus, Desulfotomaculum, Thermus* and others), as well as in Archaea (*Pyrococcus, Thermococcus, Thermoplasma, Sulfolobus* and methanogenic bacteria). It should be noted that in the latter category there are three main groups of hyperthermophiles, *viz*. the sulfide-dependent type, that metabolize sulfur to obtain energy, the sulfide-reducing type, and the methanogenic type. Almost all hyperthermophiles are sulfide-dependent and present themselves either as sulfide-oxidizing aerobes or as sulfide-reducing anaerobes, i.e. instead of using oxygen in respiration they use sulfur as an electron acceptor (they grow at temperatures above 90 °C and are mostly of marine origin). One of the most prominent known hyperthermophiles is bacterium *Pyrolobus fumarii*, which belongs to the domain *Archaea* and lives on the fumarole walls, and whose optimal growth temperature is 105 ºC, but that can grow at a temperature of 113 ºC (Fig. 33).

This remarkable feature involves stabilization of all cellular components, so that its functionality is maintained at temperatures that would be detrimental for most biomolecules of mesophile[6] organisms. Today, one of the challenges for science is to

5 They use light as a form of energy, in conjunction with chlorophyll.

6 Mesophiles are living beings who, like humans, live in a mild medium, i.e. under "normal" conditions concerning temperature and pressure, in an atmosphere containing oxygen and free of pollutants or in a neutral aquatic medium (pH around 7) in equilibrium with such an atmosphere and protected from ionizing radiation.

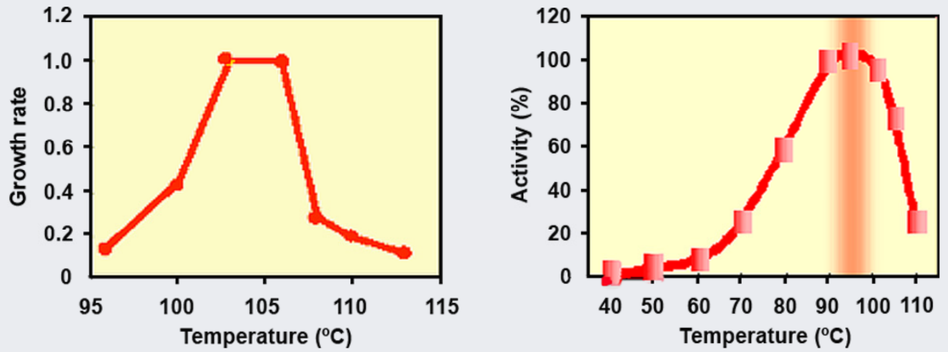


Fig. 33
Left: Growth profile of *Pyrolobus fumarii* as a function of temperature
Right: Activity profile of an intracellular enzyme of *Pyrococcus horikoshii* as a function of temperature.
Credit: N. Empadinhas *et al*., *J. Biol. Chem*., *276* (2001) 43580-43588 and H. Santos *et al*., Bol. Biotech., 69 (2001).

understand the strategies used in the stabilization of cellular components, especially proteins and nucleic acids.

The biochemistry of these organisms is adapted to operate at very high temperatures; this suggests that their proteins would be rigid, which would lead to inefficient performance of their enzymes compared to similar enzymes derived from mesophiles or psychrophiles (*cf*. 6.3 below). However, it was found that the catalytic power of enzymes of hyperthermophiles is comparable and sometimes superior to that of mesophiles. It is still largely unknown how these processes occur. It is believed that the high temperature stability of proteins is related to their various structural levels: primary structure (that of each amino acid in the amino acid sequence of the protein chain), secondary structure (internal *intra*molecular bonds, usually resulting from the involvement of hydrogen atoms — "hydrogen bonds"), tertiary structure (links through the space between atoms of the protein chain but distant from each other, often with the participation of oxygen or sulfur atoms) and quaternary structure (participation of non-proteic "motives" or association with other macromolecules — *inter*molecular bonds). Recent investigations indicate that one of the strategies used by hyperthermophiles to oppose adverse effects on the integrity of their cellular structures include the addition of external compounds, for example, organic compounds of low molecular weight that accumulate intracellularly in response to high levels of salinity and/or temperature. In addition to these characteristics, the proteins seem to have rather strong intramolecular bonds, thus showing higher stability when subjected to high temperatures. This leads us to think about the earlier mentioned Fox's microspheres, for whose formation glutamic and aspartic acids are essential, no doubt to

ensure the formation of intramolecular bonds commonly known as “cross-linking”; bonds of this type confer great stability to the molecules such as proteins.

At high temperatures DNA also undergoes denaturation, its double helix unfolds and the molecule loses its biological activity. Thus, the hyperthermophiles must have some mechanism that is capable of stabilizing the DNA molecule at these temperatures. It was discovered that the enzyme, reverse gyrase, contributes greatly to its thermal stability. This enzyme was found only in these organisms and is, to date, the only specific marker of hyperthermophilia. Many studies have been, and are being, made to further understand these remarkable microorganisms; they clearly have many “tools” and “tricks” at their disposal that enable them to live comfortably at these extreme temperatures.

6.3 Psychrophiles

WATER IS THE PRIMARY SOLVENT FOR Life and needs to be in the liquid state for Life to flourish. This condition imposes a practical limitation to growth of organisms at temperatures below 0 ºC. For this reason, the Antarctic has always been considered an environment where the existence of Life would be impossible, the extremely low temperatures typical of this continent being a serious limitation to the functioning of biological metabolism. Yet the surprising fact is that microorganisms have been found in the upper layers of ice, as well as microfossils in deeper layers. They are named psychrophiles and live optimally in temperature environments around 0 °C; they support temperatures well below 0 ºC but 20 °C is approximately the upper temperature at which they survive.

In contrast to what one might think, a stretch of ice of 5 km in length known as the Lake Vida, which lies in a region of Antarctica known as the McMurdo Dry Valleys, is far from being a place without Life. In this harsh environment, microbial life was discovered to have existed for over 2800 years, ready to continue its cycle when conditions become favorable (Fig. 34). The colonies of bacteria that live in it can survive its long low-temperature winters under hibernation conditions by accumulating solutes that can lower the solidification point of water, so preventing it from freezing. When the temperature begins to rise, heat from solar radiation is sufficient to melt small amounts of ice around dust particles, that will act as tiny solar collectors, and it is in these places that microorganisms “awake” from their hibernation and begin their short life cycles.

However, bacteria are not the only forms of Life to inhabit these places, as colonies of algae whose spores are dormant in winter and germinate in the South Pole summer were also found. Now one also knows that in “Dry Valleys” of Antarctica, once called “Death Valleys”, there are millions of microscopic plants and animals that live

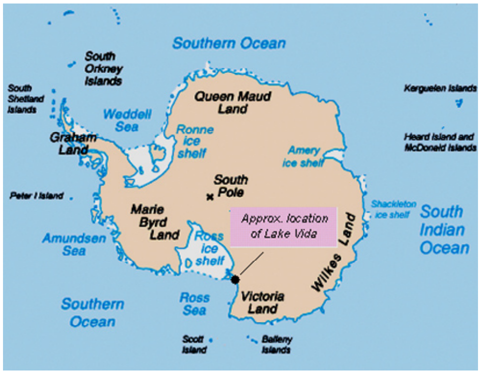


Fig. 34
Left: Bacteria of Lake Vida in Antarctica, which live buried in ice.* Right: Lake Vida in Antarctica.
* Courtesy of Priscu Research Group, Montana State University at Bozeman, USA.
URL: http://www.nsf.gov/od/lpa/news/02/pr02100_images.htm and http://en.wikipedia.org/wiki/File:Lake_Vida.png

“sheltered” in the soil, below the icy surface of lakes and even inside rocks. The abundance of living organisms present there is sufficient to establish a food chain headed by microscopic nematodes; according to some researchers this is the simplest ecosystem on the planet. As a mechanism for adaptation to such a rigorous environment when it becomes too cold and dry, nematodes enter a state of dormancy, called anhydrobiosis, in which they lose up to 99% of their body water. Other inhabitants of the Dry Valleys are cyanobacteria, which exist in appreciable quantities in lakes. This discovery may help the investigation of ecosystems that are possible in places previously thought to be incompatible with Life, such as the famous Lake Vostok, an ancient lake, discovered, at a depth of 4 km, beneath the East Antarctic ice plate.

6.4 Halophiles

HALOPHILES LIVE IN NATURAL ENVIRONMENTS such as the Dead Sea, in pools of seawater in which the concentration of sodium chloride (NaCl) is very high (around 25%) or in salt-marshes created by man. Such environments are also highly alkaline due to the release of ions by sodium carbonate and other salts. These organisms require salt in order to grow, but if they had not developed forms of resistance to the desiccation that would result from the difference in salinity of its external environment and its cytoplasm, they could not survive. There are two types of strategies for adapting to this type of environment, *viz.* structural changes of their cell walls, ribosomes and proteins, and stabilization of these structures by the accumulation of certain types of stabilizing materials.

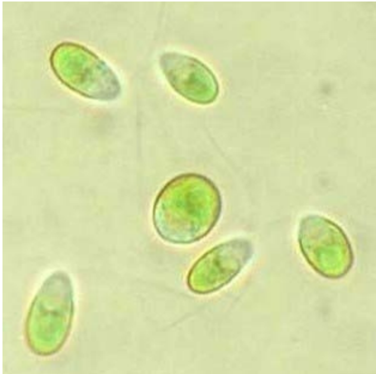


Fig. 35
Dunaliella salina, a halophilic bacterium
Courtesy of Oilgae, Tamilnadu, India.
URL: http://www.oilgae.com/ref/glos/dunaliella.html

The stability of the cell wall of extreme halophiles is maintained in two different ways. Gram-positive cells of species of the type *Halococcus morrhuae* have a wall consisting of a sulfide heteropolysaccharide,[7] which is stabilized by high concentrations of sodium. Some of the adaptations of extreme halophilic organisms as, for example, those of archaeons of the *Halobacteriaceae* family or of bacteria of the *Haloanaerobiales* family, involve accumulation of inorganic ions such as sodium (Na^+), potassium (K^+) and/or chloride (Cl^-), in high concentrations to counteract the external osmotic pressure and maintain cell integrity; in the type *Halobacterium* their cell wall contains glycoproteins[8] with a high number of amino acid units with negative electric charge,[9] which are stabilized by interaction with sodium ions of the external environment. With regard to proteins, they contain a greater percentage of amino acid residues (units) with negative electric charge, and the catalytic capacity of enzymes is dependent on the presence of salts. If on the one hand this strategy of building up high levels of inorganic salts allows extreme halophiles to occupy an environmental niche virtually inaccessible to other microorganisms, it inevitably restricts them to this niche, making it impossible for them to colonize other regions of more moderate salinity or to major changes in salinity.

Moderately saline habitats can be colonized by moderate halophiles whose adaptation strategies are based not on accumulation of inorganic salts, but on that of certain organic compounds imported from the medium or produced by them; the role of these compounds is to ensure the balance of osmotic pressure on the cell walls. In this way, the

7 A heteropolysaccharide is a compound structurally similar to cellulose, which is a homopolysaccharide, but whose molecule is composed of different sugar units, as the name indicates.

8 In addition to units derived from amino acids, the molecules of glycoproteins incorporate units derived from sugar.

9 Aspartic acid, glutamic acid and cysteine are called negative electric charged amino acids because in heavily saline and moderately alkaline media they give rise to their respective salts (sodium or other) in the form of aspartate, glutamate and cysteinate, with the formation of negative charges along the protein chain.

microalgae *Dunaliella*, uses glycerol (Fig. 35).[10] Accumulation of organic solutes is a very efficient and effective mechanism in the adaptation of most halophilic microorganisms in that it does not affect the components of the cell and allows the organism to react with versatility to changes in the salinity of the medium, still protecting the cells from moderate thermic attacks.

The organisms of the type *Halobacterium halobium* living in the outskirts of tropical seas are usually aerobic and heterotrophic. However, the high concentration of salt in their habitat limits the availability of oxygen for breathing, mostly in the case of organisms that are located at a greater distance from the surface. To circumvent this deficiency, they develop a "purple membrane" that is composed of regions containing a light absorbing pigment. This pigment is a type of rhodopsin[11] called bacteriorhodopsin, which produces a concentration gradient of protons in the membrane and helps to balance the excess of osmotic pressure on the cell walls caused by the saline medium. The energy meanwhile absorbed by this mechanism allows this microorganism to synthesize ATP[12] in the absence of oxygen.

6.5 Acidophiles and alkalophiles

Acidophiles are living beings that are adapted to environments with extreme values of acidity (pH below 7, but typically between 0 and 4) and are actually unable to proliferate in neutral or near neutral media. These extremophiles grow in environments where acid occurs from natural geochemical activity or from their own metabolic activity. An extraordinary example of a very acid medium is that found in Rio Tinto, in the Spanish province of Huelva, where there is a remarkable ecosystem that is being studied by NASA astrobiology researchers. Since its water is very acidic (pH around 2) and contaminated to a high degree with iron, this river would be apparently inappropriate for survival of any organism. However, contrary to expectation, Rio Tinto houses a colony of more than 1,300 different species of acidophilic microorganisms (including bacteria, yeasts, fungi, algae and protists) that feed on polymetallic sulfides. DNA molecules do not withstand media whose acidity differ from neutrality, and the way that acidophiles defend themselves from the environment is to protect the inside of the cell with defensive molecules placed in their cell walls that support contact with the acidic medium, thus keeping the pH of the interior between 5 and 7. The *Ferroplasma acidarmanus*, an extreme acidophile found with many others in the Richmond Mine, California (USA), is among the most

10 Glycerol is the trialcohol $CH_2OH\text{-}CHOH\text{-}CH_2OH$, commonly known as glycerin, and is used by all cells for the construction of cellular membranes.

11 Rhodopsin is a proteic pigment that is associated with the organs of vision and that works especially in the night vision.

12 ATP is an acronym for adenosine triphosphate (Adenosine TriPhosphate), a derivative of adenine that is generated from the respective diphosphate (ADP); it operates in living beings as if it were an accumulator of energy, which is released when ATP turns again into ADP.

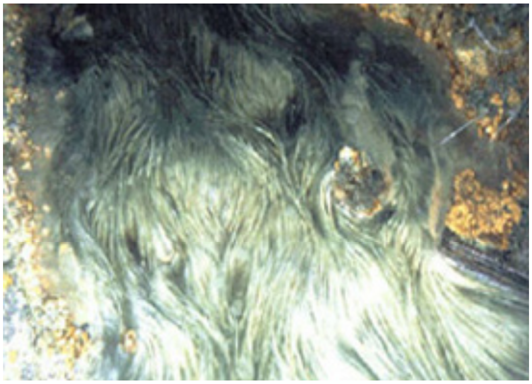


Fig. 36
Ferroplasma acidarmanus from the Richmond Mine (California).
Credit: US Department of Energy Joint Genome Institute.
URL: http://genome.jgi-psf.org/draft_microbes/ferac/ferac.home.html

amazing extremophiles; indeed, it metabolizes iron sulfide, transforming it into sulfuric acid, which creates a medium similar and as corrosive as the inside of car batteries, at a pH value around zero (Fig. 36)!

The living beings that inhabit alkaline environments (pH above 7, but typically between 10 and 10.5) are known as the alkaliphiles (Fig. 37). They are found in soils rich in carbonates and in saline lakes such as Lake Nasser in Egypt and the Lake Natron, in Kenya. These microorganisms raise interesting questions, especially regarding bioenergetics and the mechanisms that allow them to maintain such high transmembrane proton gradients. The *Natronobacterium gregory* is both an alkalophile and a halophile. The in-

Fig. 37
Cluster of cells of *Halobacterium* sp. strain NRC-1.
Credit: NASA.
http://en.wikipedia.org/wiki/File:Halobacteria.jpg

tracellular pH of alkalophiles remains between 7 and 9, i.e. their cytoplasm has a pH value similar to that of neutrophiles.[13] Like acidophiles, the intracellular components, such as proteins, do not require specific strategies to adapt. At least in some species this balance is maintained by exchange of protons (H^+) with sodium ions (Na^+), which are then recovered by absorption of salts from outside the cell. However, many questions remain with regard to the mechanisms that act on these organisms.

6.6 Radiophiles

THE ORGANISMS THAT PROLIFERATE IN environments with high levels of ionizing radiation such as UV and gamma radiation are called radiophiles. The *Clostridium* and *Deinococcus radiodurans* (Fig. 38), found in nuclear waste resist radiation doses of up to 15,000 Gy,[14] when most living beings are exterminated at doses ten times smaller. Indeed,

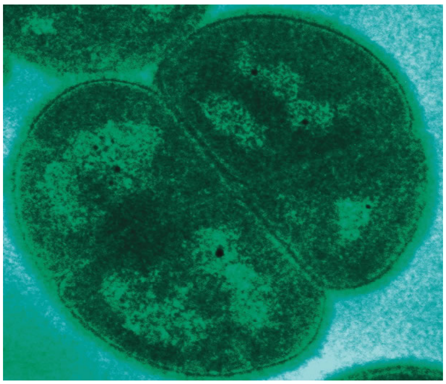


Fig. 38
Photomicrograph of *Deinococcus radiodurans*, a radiophile that can be found in nuclear waste.
Credit: The Oak Ridge National Laboratory.
URL: http://en.wikipedia.org/wiki/File:Deinococcus_radiodurans.jpg

when exposed for a short period of time the lethal dose[15] for humans is 4–10 Gy, for the bacteria that inhabit the intestines of humans, such as *Escherichia coli*, it is 60 Gy and for the fruit fly it is 600 Gy; the annual dose of radiation received in natural environments at the Earth's surface does not exceed 0.2 Gy.

By promoting the breakage of chemical bonds, ionizing radiation tends to destroy most of the chemical material of all living beings, altering the cell membrane, the enzyme

13 Neutrophiles are organisms whose habitat is neutral (neither acid nor basic), characterized by pH = 7.
14 Gy = gray is the amount of energy of ionizing radiation, in joules, absorbed per kilogram ($J\ kg^{-1}$).
15 Lethal dose is the amount of radiation that in a period of 30 days causes death in 50% of a population.

system, the energy metabolism and, especially, its RNA and DNA; the genetic material is the most affected because it undergoes fragmentation when exposed to radiation. *Deinococcus* bacteria have been extensively investigated in order to reveal the mechanisms that enable them to withstand such damage; however, many doubts still exist. Apparently two mechanisms may operate, *viz*. duplication of genetic information and reconstruction of DNA by the action of one or more specific enzymes. The latter occurs when the DNA of these species possesses genes which encode proteins that carry out the repair, and as it would appear, their DNA is very tightly coiled up thus preventing dispersion of the fragments before they are linked by action of these enzymes.

It is also interesting to note that temperature, high acidity or dryness can cause damage to genetic material, which in extremophiles is repaired by the action of enzymes by the described mechanism. Thus, it is not surprising that radiation-resistant microorganisms are also resistant to high temperatures, oxidative damage and highly acidic or dry environments.

6.7 Barophiles and piezophiles

IT IS USEFUL TO DISTINGUISH BETWEEN barotolerant beings and barophile beings. The depth of the oceans is, on average, about 4000 meters, but the place of greatest depth is called Challenger Deep, located east of the Philippine Islands, in the Mariana Islands, and increases to about 11 000 meters; it is known that there is ocean life even in this deep region. Pressures at such depths are 400 and 1100 atmospheres, respectively, in relation to the pressure at sea level. Many oceanic organisms that inhabit the shallower waters can be found down to depths of 4000 meters; although they are able to withstand the high pressures associated with such depths, they grow best at a pressure of one atmosphere; these are called barotolerants. However, microorganisms that live in deeper water, i.e. 5000–6000 meters, grow best at high pressure and are truly barophiles; however, those whose habitat is located below the 6000 meters and that do not grow at a pressure of one atmosphere are considered hyperbarophiles. The microorganisms of Challenger Deep may grow at pressures of between 700 and 800 atmospheres, but cannot survive pressures of less than 50 atmospheres. Phylogenetic analysis of microorganisms that inhabit these places point to the presence of bacteria of the genres *Shewanella* (Fig. 39) and *Moritella*.

The organisms that live at these pressures are almost incompressible, i.e. their volume is little affected even by large changes in pressure. However, small changes in volume due to their moving to depths different from those that are optimal, may inhibit some of their chemical reactions. For example, when the pressure increases, the molecular constituents of the cell membrane become compressed, and this results in a decrease of membrane fluidity. Thus, organisms that tolerate large pressures need to adapt the composition of their cell membranes to increase their fluidity.

Fig. 39
Shewanella oneidensis a barophile that inhabits the Marianas pit at the abysmal depth of 11 000 m.
Credit: Oak Ridge National Laboratory, U.S. Department of Energy.
URL: www.ornl.gov/info/ornlreview/v37_3_04/article02.shtml

In order to eject any organism into interplanetary space, a sufficiently large impulse must be applied for it to reach the escape velocity and thus overcome the force resulting from the gravitational pull of the planet. This impulse corresponds to such an acceleration that the weight of the body concerned greatly increases; in the case of a soft body, its parts are compressed as if they were subjected to great external pressure. To test the possibility of their ejection from a planet into interplanetary space, various microorganisms, including *Deinococcus radiodurans*, have been subjected to tests of pressure to produce similar increases of weight. These tests have been performed by ultracentrifugation at 100,000 rpm[16] (about 400,000 G[17]) and also by shooting with rifles (about 4,000,000 G) in which the microorganisms are placed inside the cavity of lead projectiles (commonly called "lead shots"). Between 40 and 100% of the microorganisms subjected to such tests resisted. Similar results have been obtained in experiments at an impact speed of 5 km per second to test the resistance to the pressure experienced at the moment of impact of microorganisms coming from space. These features cause these microorganisms to be described as "hyperpiezotolerants".

6.8 Xerophiles

WATER POSSESSES MANY PROPERTIES that make it a solvent essential to Life. The loss of small portions of intracellular water can be lethal to many cells, but there are certain organisms that can survive extreme desiccations, even for long periods of time.

16 Rpm = revolutions per minute.
17 The gravitational unit is represented by "G" and is equal to the gravitational acceleration on Earth; 1 G = 9.8 meters per square second (m s^{-2}).

Fig. 40
Xerophile shrimps of the gender *Artemia salina*.
Credit: Alaska Fisheries Science, National Oceanic and Atmospheric Administration.
URL: http://pt.wikipedia.org/wiki/Ficheiro:Artemia_salina.jpg

Organisms that are capable of living in extreme drought change from colonies of bacteria to colonies of symbiotic algae in lichens; some fungi, plants, insects and nematodes, and even tardigrades and the shrimp *Artemia salina*, are also capable of living under the same conditions of extreme drought (Fig. 40).

The mechanisms of desiccation that lead to death include irreversible changes, such as denaturation and rupture of the lipid, protein and nucleic acid structures. They also include accumulation of reactive oxygenated species during dehydration, especially under sunlight. Thus, the beings that can tolerate extreme desiccation defend themselves by anhydrobiosis, a state that is characterized by only a small amount of intracellular water and by non-occurrence of metabolic activity.

6.9 Polyextremophiles

LIVING BEINGS THAT INHABIT ENVIRONMENTS, or resist physical and chemical conditions, that for more than one reason would be lethal to humans and to those beings closely related to them are currently designated polyextremophiles. It was mentioned above that radioresistant organisms also resist high temperatures, oxidative damage and highly acidic or highly dry media. Thus, the *Deinococcus radiodurans* is actually a polyextremophile, as are the majority if not all of living ecosystems associated with oceanic hydrothermal springs. Indeed, they all support the high pressures of the deepest ocean regions and most resist high temperatures, high concentrations of chemical materials, lack of oxygen and absence of light, characteristics typical of those places. But the polyextremophiles are not necessarily exclusive of submarine hydrothermal sources. The psychrophiles that inhabit the interior of

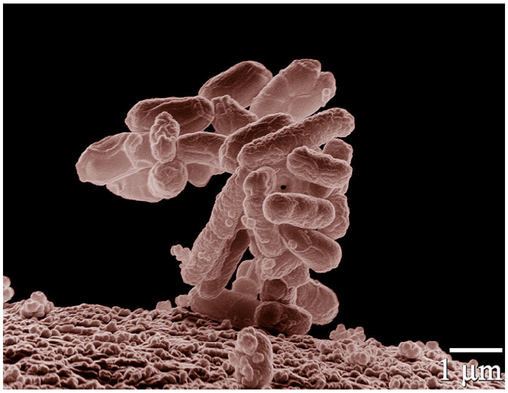


Fig. 41
Low-temperature electron micrograph of a cluster of *Escherichia coli*, magnified 10,000 times.
Credit: Eric Erbe and Christopher Pooley, USDA, ARS, EMU.
URL: http://pt.wikipedia.org/wiki/Ficheiro:E_coli_at_10000x.jpg

Antarctic rocks are also endolites and, at least in some cases, also methanogenic, as their metabolism involves methane. The bacteria *Escherichia coli* (Fig. 41), which inhabit the intestines of animals, are also polyextremophiles, as they are methanogenic, anaerobic and live in the dark; the same can be said of *Helicobacter pylori*, that inhabit the human stomach, as they are acidophiles, anaerobic and live in the absence of light.

When Life arose on Earth the physical and the chemical environment on the surface of the planet was quite different from the present day. Arising out of physics, chemistry and biology, and several earth sciences, a variety of branches of science have striven to unravel how such an environment can be characterized. Despite some uncertainty, it is now possible to speculate as to how it was; it is certain that the primitive Earth's environment would be so harsh (in today's terms) that only extremophiles would be able to resist and spread Life into the present age. The microorganisms that transform the soil and make it fertile, digesting the remnants of the dead organisms and turning them into material assimilable by other beings, live in the interior of the soil, away from light and oxygen, (which would be fatal to them), and they metabolize methane — they are methanogens. Methane would have perhaps been abundant in the early Earth's atmosphere when oxygen was absent, and the soil would be an excellent medium to provide protection from the intense UV radiation from the Sun, unfiltered by an ozone layer then non-existent — an optimum environment for methanogenic species in the soil. But what importance would protection from UV radiation have, if any radiophile, or at least radiotolerant species, could populate the planet surface, as much as it would also resist the possible aggression of a medium saturated with chemical materials from space and potentially too hot or too cold? These microorganisms are *Archaea* and, therefore, would count amongst the oldest inhabitants of the planet.

The early Earth may not have been much different from planet Mars in its early years, or from the present conditions of the satellites of some of the other planets, particularly Jupiter and Saturn. May they have harbored or still harbor some forms of Life that one would call extremophiles? Will piezophiles have travelled or still travel from planet to planet, spreading Life in all of them? Could Life have first emerged in another planet, or even an asteroid or comet, and only later flourish on Earth, when the natural evolution of the Solar System made this planet the most hospitable of all? These are questions that remain open, but to which we will return later. Irrespective of whether Life appeared first on Earth or not, the question of its origin still stands; this will be discussed next. But before starting, let us point out that the extremophiles we have come to know on our planet, particularly the hyperextremophiles, have directed us outside our planet in our search for the origin of Life. Seeking its origin on Earth is far too restrictive, one has to examine the whole Solar System, and indeed the entire Universe!

SECOND PART

The current investigation of the origin of Life

Introduction

Progress in science is achieved only by placing brick over brick and not by building suddenly fantastic palaces.[1]

Fig. 42
Sombrero Galaxy M104 photographed by the Hubble Space Telescope.
Credit: NASA/ESA and The Hubble Heritage Team STScI/AURA).
URL: http://antwrp.gsfc.nasa.gov/apod/ ap070121.html

STARS ARE FUNDAMENTAL CONSTITUENTS of the Universe, huge balls of gas at very high temperature, mostly formed by protons, electrons and neutrons; protons are nuclides of the simplest chemical element that exists in nature, hydrogen. Stars generate their own energy through nuclear reactions that produce new, successively heavier nuclides by fusion of the lighter ones with each other, in a process known as stellar nucleosynthesis. A star is something akin to a nuclear reactor generated by its own gravity. The giant nuclear reactor — the core of the star — synthesizes nuclides of helium and heavier elements from hydrogen nuclides. Gravity acts inexorably, compressing the star until it exhausts its energy source. Small-mass stars will die gradually, cooling slowly and increasing in size; the high-mass ones explode in a violent way, spreading the nuclides processed in its core throughout the interstellar medium.

During most of a star's life (the main sequence stage), the hydrogen nuclides[2] at its core at a temperature of 15×10^6 K undergo fusion with each other via the proton-proton nuclear reaction to form helium nuclides. When the helium core reaches a mass of about 15% that of the star it becomes unstable and starts to shrink, and the core temperature increases greatly. At this point the star moves from its main sequence stage towards the

1 Julian S. Huxley (1887–1975), British evolutionistic biologist.
2 A nuclide is a species that has real existence under certain conditions, corresponding to the nucleus of an atom, i.e. an atom to which all its electrons had been removed.

red giant stage. When the core reaches a temperature of 100×10^6 K, fusion of the helium nuclides begins.[3] This produces carbon nuclides, around which there is a shell where hydrogen is still producing energy. The star begins to swell to about 250 times its original size, its surface temperature cools and it becomes a red giant. At the end of this phase the star may lose most of its outer layers forming a diffuse cloud of gas and dust known as a planetary nebula.

Stars of greater initial mass age more rapidly. Gravitational collapse leads to many higher mass nuclides, e.g. carbon, oxygen, nitrogen, magnesium and as heavy as, but not heavier than, iron, being formed. Gravitational collapse can be extreme leading to a massive *supernova* (plural *supernovae*, from Latin) outburst, which distributes nuclear material throughout the surrounding space, together with accelerated electrons and neutrons. When the latter collide with the dispersed nuclides, new nuclides heavier than iron are generated (explosive nucleosynthesis). Some outbursts are not as massive as *supernovae*; these are known as *novae* (singular *nova*).[4]

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3 Initially this process is explosive, which supports being called ignition.

4 After a *supernova* of a low mass red giant star, what remains is a white dwarf; the remains after a *supernova* of a large mass red giant is a neutron star or a pulsar or a black hole.

Chapter 7

Interstellar Chemistry

The beginning of knowledge is the discovery of something we do not understand.[1]

Fig. 43
Cone Nebula. Cloud of gas and dust that genarates new stars. Image obtained by the Hubble Space Telescope.
Credit: ACS Science & Engineering Team, NASA.
URL: http://apod.nasa.gov/apod/ap040529.html

As matter escapes the gravitational influence of its original stars during cooling processes that lead to red giants or white dwarfs, or other bodies by ejection during cataclysmic processes such as *novae* and *supernovae*, interstellar space becomes enriched with ions. These new species will lose speed as they migrate from where they were ejected; when their temperature drops to 3000 K, they may acquire one or more electrons to become neutral atoms of elements. One may thus say that, with the exception of hydrogen and some of the pre-existing helium,[2] all elements that surround us, as well as those that constitute our molecules, have their origin in stars. The material ejected by a star by any of the above mechanisms remains initially scattered into clouds of gas and dust. Nevertheless, however widely dispersed they may be, these atoms and atom-clusters

1 Frank P. Herbert (1920–1986), North-American writer of science fiction.
2 The nucleus of the hydrogen atom is one of the elemental particles, the proton, and was generated after the "Big-Bang" Some of the helium of the Universe was formed by nucleosynthesis also as a consequence of the "Big-Bang" and before the stars had formed.

exert gravitational attraction on each other, which during the immensity of cosmic time inevitably brings them closer and closer together, resulting in dense clouds of gas and dust. Later, these dense clouds can lead to new stars in the vastness of space, completing, therefore, an extensive cosmic cycle. However, despite the very low temperatures and the huge emptiness of space into which these interstellar atoms are initially projected, they are able to interact and give rise to molecules, some of remarkable complexity that can act as precursors in the formation of matter as complex as that associated with living beings.

7.1 Gas and dust involvement

One of the most important discoveries of the last decades of the 20th century was that of organic compounds in interstellar clouds of cold gas. Among the many compounds detected (currently more than 140 different species of neutral molecules and ions), common molecules such as methanol, formaldehyde, acetic acid, ethanol, benzene and glycolaldehyde, as well as less common chemical species containing many carbon atoms, such as the species C_8H and $C_{11}NH$, are included. In addition to these astronomical observations, the analyses of meteorites have revealed the presence of organic species such as nitrogen bases (purines, pyrimidines[3]) and amino acids. The nitrogen bases are essential components of nucleotides of DNA and of RNA, and amino acids are the monomers from which proteins[4] are formed; so, the molecules thus found are fundamental to Life as we know it.

The positive results of the Urey-Miller and Fox experiments, amongst others, veil the fact that the conditions the researchers artificially created for production of organic matter differ significantly from the current thinking regarding the atmosphere of the early Earth. Although there is liquid water on Earth, and temperature and environment favor the emergence of Life, paradoxically most of the organic matter in the Solar System is outside the Earth (there being large quantities in comets, asteroids and in giant planets and their moons). Through these discoveries, it is not surprising that the study of organic chemistry in space is an area of very active research, that has created a feasible alternative to the hypothesis of purely terrestrial life (the endogenous hypothesis).

The interstellar medium is the space between the stars. This space is characterized, in general, by its low density and temperature, although in some regions one may find high densities and temperatures. The interstellar medium is fed, as referred to above, by the stellar atmospheres and is in continuous contact with them. In this highly

3 Guanine and adenine belong to the class of purines; thymine, cytosine and uracil belong to the class of pyrimidines.

4 Proteins are the building blocks of cells and play a crucial role in all biological processes, performing the following functions: structural, enzymatic, transportive, hormonal, immunological, producing coordinated movement and providing food reserve.

variable environment many different types of molecules, radicals[5] and ions are found; in other words, the composition of the interstellar medium is highly anisotropic.

The chemical species present in the interstellar medium can be precisely identified from their spectra obtained by spectroscopes attached to telescopes. Atoms emit highly energetic photons when their electrons relax moving spontaneously to lower energy levels after having been excited to high levels of energy by photons received from any light source, typically UV or visible light. Molecules have a more complex structure that allows other forms of emission associated with significantly lower energies, usually in the IR and microwave regions. Molecules as a whole can rotate and the nuclei of their atoms can vibrate with respect to their position of equilibrium. The variations of energy associated with rotation are very small and the energy of the photons produced lies in the microwave band. Detection of these photons plays a key role in astrophysics, as it enables the study of the cold gas from which the stars are formed. The variations of energy associated with molecular vibrations produce photons in the IR; detection of these photons allows study of the proto-stellar and proto-planetary systems whose temperatures are around 30 K or larger. In this way, while the more energetic electronic transitions of atoms allow the study of stars, the rotational and vibrational transitions of molecules allow probing and exploring of the interstellar regions, and even a determination of their chemical conditions.

Much current research consists in preparing laboratory mixtures of compounds that are believed to exist in a given interstellar region and examining them by spectroscopy while their composition is being modified to generate a spectrum identical or very similar to that obtained from interstellar space. By means of laboratory simulation experiments not only has information been obtained on the chemical composition of regions of the Universe many light-years distant from us, but also the presence of compounds that had not yet been detected in these regions have been discovered. Figure 44, on the next page, shows an infrared image of a galaxy 12 million light years distant from us revealing the presence of polycondensed aromatic hydrocarbon (PAHs[6]) (Fig. 44).

Between the years 1937 and 1941 the first three interstellar species, i.e. radical cyanogen (CN), methylidene radical (CH) and methylidenium cation (CH^+) were identified by their spectral lines. In 1963, the hydroxyl radical (OH) was found by radio astronomy, and in 1968, water and ammonia were detected. Such findings then became more and more frequent, due mainly to the use of increasingly sophisticated instruments. It is pertinent that three quarters of the interstellar molecules identified are organic molecules of very many types, such as hydrocarbons, alcohols, acids, aldehydes, ketones, amides, esters and ethers,

5 In chemistry one labels "radical" (or "free radical") to a group of atoms where the valence rules are not satisfied. In other words, it is an incomplete molecular species that in dense media, i.e. at pressures as high as the atmospheric pressure on the Earth's surface, usually is short-lived because it reacts very quickly with an identical species or with other species to generate a complete molecule; but it can be very long-lived at the very low pressures and densities of the sidereal space.

6 PAH is an acronym for Polycondensed Aromatic Hydrocarbon; its molecules are composed of sets of planar hexagonal rings linked together side by side, i.e. they are planar molecules formed by carbon atoms distributed as a honey-comb; each carbon atom on the periphery of these molecules is also bonded to a hydrogen atom.

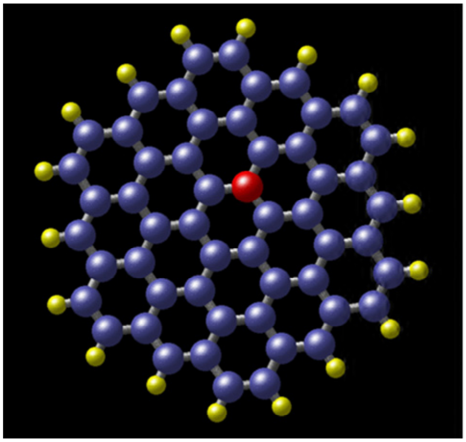


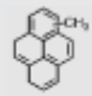
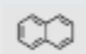
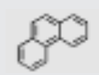
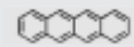
Fig. 44
Left: Model of a polycyclic aromatic hydrocarbon (PAH) containing nitrogen. The blue balls are the carbon atoms that make up the skeleton and the yellow balls are hydrogen atoms attached to the periphery. The red ball shows the position of a nitrogen atom, which fits almost perfectly within the molecule.
Right: Spitzer Spece Telescope image of the spiral galaxy M81 located some 12 million light years from Earth. The infrared radiation emitted by polycyclic nitrogen-containing aromatic hydrocarbon (PANH) molecules is shown in red.
Credit: NASA, Ames Research Center.
URL: http://www.nasa.gov/centers/ames/multimedia/images/2005/spitzer.html

organo-sulfur compounds, acetylene derivatives and derivatives of paraffins with the group CN, amongst others.[7] PAHs were discovered for the first time in the year 1980. Currently it is thought that these hydrocarbons or their cations are responsible for the DIBs ("Diffuse Interstellar Bands"), intense emission of radiation in the form of bands in the UV, visible and near IR, known since the 19th century, and a long standing problem of interpretation. The table on the next page displays the similarity between DIBs and the spectra of PAHs obtained under laboratory simulation.

Molecular clouds are affected by cosmic and UV radiation, the latter coming from stars, which provide the energy necessary to initiate activation of many chemical reactions between different species, promoting the combination of atoms between themselves and the breakage of bonds in molecules, ions and radicals; this may lead to new and possibly more complex molecular species. There are two models that explain this mechanism: the model of catalysis and the collisional model. Formation of molecular hydrogen is explained by a mechanism of catalysis where dust grains act as catalysts. The hydrogen atoms, which predominate in the interstellar matter, are adsorbed on the surface of grains by the action of weak forces of cohesion. Their very small size imparts them with high mobility, thereby favoring encounters (col-

7 It is possible to obtain from Internet updated lists of the molecules found in the stellar and circum-stellar space; the compilation kept updated by D.E. Woon, at http://www.astrochymist.org/astrochymist_ism.html is especially recommended.

Comparison of Dibs with PAHs by spectroscopy*

$PAHs^+$		λ_{max} (nm)	
		$PAHs^+$	DIBs
Pyrene$^+$ ($C_{16}H_{10}^+$)		439,5 (443,0no ar)	442,9
1-Methylpyrene (CH_3-$C_{16}H_{10}^+$) 4-Methylpyrene (CH_3-$C_{16}H_{10}^+$)		444,2 (457,7) 482,8 457,6	442,9 482,4 458,1
Naphthalene$^+$ ($C_{10}H_8^+$)		674,2 652,0	674,1 652,0
Phenanthrene$^+$ ($C_{14}H_{10}^+$)		898,3 856,8	857,2
Tetracene$^+$ ($C_{18}H_{12}^+$)		864,7	864,8
1,12-Benzoperylene$^+$ ($C_{22}H_{12}^+$)		502,2 758,4 755,2 794,3	503,9 (?) 758,4; 758,6 755,8 (?); 756,2 793,5 (prov.)
Coronene$^+$ ($C_{24}H_{12}^+$)		459,0 946,5	449,5 946,6

* F. Salama, Astrochemistry Laboratory, NASA Ames Research Center (http://www.nasa.gov/centers/ames/home/index.html).

lisions) on the surface of the grains. These encounters lead to formation of molecular hydrogen (H_2). The small size of the hydrogen molecule and the consequent weak interaction with the grain will facilitate its subsequent expulsion into space. The sub-microscopic carbonaceous and silicate grains in the interstellar medium also play an important catalytic role, because in the high vacuum of outer space triple collisions of atoms or molecules cannot occur except on the surface of solid grains. Thus, the surface catalysis model plays a key role not only in the synthesis of molecular hydrogen, but also in the synthesis of more complex molecules.

In the interstellar space there are regions with different densities of matter, that lead to a distinction between two types of environments: the dense ("Interstellar Dense Molecular Clouds") and diffuse ("Diffuse Interstellar Medium" — DISM). The collisional model con-

siders that the chemical reactions result from collisions between reactive species. On causing ionizations in atoms and molecules, the UV radiation in diffuse clouds and cosmic rays in dense clouds play a fundamental role in these reactions, as they allow them to occur by a 'domino effect'. Thus, after the primary ionization of hydrogen and helium, a whole range of reactions take place by different mechanisms — radiative association, ion-molecule reaction and ion-electron reaction — leading to more complex molecular species, including hydrocarbons, each with release of energy in sufficient quantity to promote new reactions.

Distinction between dense clouds and diffuse clouds is relevant from a chemical point of view, as the type of chemistry that occurs in each is quite different. As they do not fully obscure the light from stars that are behind them, diffuse clouds can be studied by analyzing the absorption spectra of visible light emitted by stars. These clouds are astrophysical entities that are simpler than the dense clouds, but their chemistry is more complex, because of the occurrence of photoionization and photodissociation, processes which are absent in dense clouds owing to their opacity to UV radiation. Because of the greater density in dense clouds, the frequency of collisions is higher than in diffuse clouds, which means that there is a greater probability of chemical reactions occurring between their constituents, resulting in relatively rapid responses and production of increasingly complex species.

Most of the material of diffuse clouds is in the form of gas and dust grains (Fig. 45), since only the most stable molecules survive exposure to the high energy radiation that reaches this medium. The grains will be able to adsorb on their surface some gaseous species (atoms and molecules) that are present in the cloud. Thus, one can visualize a grain of interstellar dust as consisting of a core containing silicates (and possibly magnesium oxide) and a crust formed by adsorbed species (e.g. atomic and molecular hydrogen, nitrogen, carbon and oxygen atoms, and also water and other hydrides). Studies by IR spec-

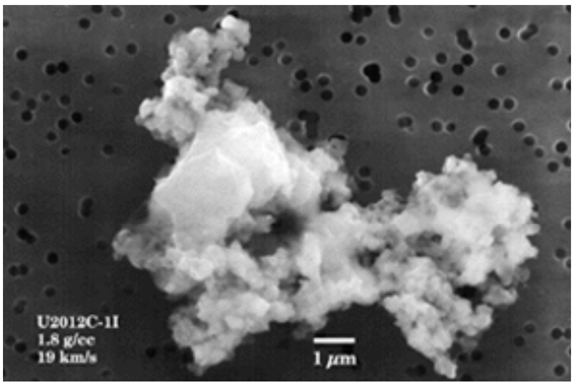


Fig 45
Dust grain collected at 510 km above Earth's surface by NASA LDEF mission and brought in 1990 by space-shuttle Columbia.
Credit: NASA, LDEF, SETAS.
URL: http://www.meteoriticalsociety.org/newsimages/IDP.jpg

troscopy of PAHs have suggested that they are quite stable species — they are ionized by the radiation but do not decompose.

Dense clouds have extremely low temperatures, typically between 10 K (–263 ºC) and 50 K (–223 ºC) and, therefore, the majority of compounds are found in the form of ice. These interstellar ices are primarily made of water ice, but also ices based on carbon monoxide, carbon dioxide, methanol and ammonia. Compared to diffuse clouds, the density of the material of these dense clouds is very large. The regions called Sagittarius B2 and Orion Bar, which are rich in organic material, have been much investigated, particularly by microwave spectroscopy in the search for new interesting molecules from the viewpoint of chemical evolution. In 2000, the existence of glycolaldehyde, the simplest sugar, was found in Sagittarius B2, at 26,000 light-years from us (Fig. 46). This finding is compatible with the fact that in 2001, polyalcohols and di-hydroxyacetone, were found in the Murchison and Murray meteorites — the former are related to and the latter belongs to the sugar family.

7.2 The chemistry of carbon

Carbon is one of the most abundant elements in the Universe and its chemistry plays a key role in the Cosmos, since Life, as we know it, is based on the ability of this element to connect with itself and with many other elements. The high abundance of carbon over that of oxygen dominates the chemistry of any region of the interstellar and circumstellar media. When oxygen is more abundant than carbon, almost all of the latter

Fig. 46
Left: molecular hydrogen (H_2) in a region about 3 light-years wide of Sagittarius B2.*
Center: radio telescopes 12 meters in diameter at Kitt Peak, Arizona, U.S.A.†
* Credit: R. Gaume, M. Claussen, C. De Pree, W.M. Goss, D. Mehringer, NRAO, AUI, NSF. † Credit: NRAO.
URL: http://www.nrao.edu/pr/2000/sugar
Right: Molecular model of glycolaldehyde, the simplest sugar,
found with radio telescopes in Sagittarius B2, in the year 2000.

will be in the form of carbon monoxide (CO) and the remainder may be in the form of water (H_2O), oxides and other compounds. However, when carbon is more abundant than oxygen, in addition to carbon monoxide a wide variety of organic molecular species will be generated. In older stars that are impoverished in hydrogen, carbon forms complex chains such as *baton*[8] molecules, PAHs and heteroaromatic compounds.[9]

It is noteworthy that PAHs, fullerenes[10] and tars were also discovered in meteorites; fullerenes have the ability to contain within them molecules of other types, which gives them the potential to act as possible vehicles for transportation to Earth of prebiotic material. Furthermore, analysis of fullerenes extracted from meteorites and from their impact craters has revealed trapped atoms of helium (He). The abundance ratio of its two isotopes, helium-3 (^3He) and helium-4 (^4He), contained in these fullerenes is ten times larger than that found on Earth, which confirms their extraterrestrial origin.[11]

Forms of carbon in the interstellar medium

Localization	Atoms and molecules	Solid species
Circumstellar shells around red giant stars	Carbon monoxide, acetylene, complex hydrocarbons, PAHs in the gas phase	Non-graphitic carbon, silicon carbide (SiC)
Diffuse interstellar medium	Carbonium ions (C^+), simple diatomic molecules, PAHs in the gas phase, carbon chains	Graphitic material, carbonaceous solids with aliphatic hydrocarbons
Dense interstellar medium	Carbon monoxide, complex hydrocarbons	Ices containing carbon (carbon monoxide and dioxide, and methanol), coagulated carbonaceous grains
Interstellar material in primitive meteorites	PAHs	Carbides, graphitic grains, poorly graphitized carbon, spheroidal carbon, nanodiamonds

8 Linear molecules consisting of a sequence of carbon atoms with an atom of hydrogen at one of its ends and a nitrogen atom at the other end (the following is the largest that has been found to date, somewhere in the circum-stellar region of an old red star: H–C≡C–C≡C–C≡C–C≡C–C≡C–C≡N).

9 PAH-type compounds, in which carbon atoms (one or more) are substituted by atoms (one or more) of other elements (mainly nitrogen and/or oxygen).

10 Fullerenes are spherical, ellipsoid or cylindric molecules composed entirely of carbon atoms; the most common fullerene has 60 carbon atoms connected together and arranged according to a structure that is reminiscent of a football.

11 In the interstellar medium this ratio, $^3He \div {}^4He$, is 1:100,000; in the Earth's atmosphere its value is 1:1,000,000.

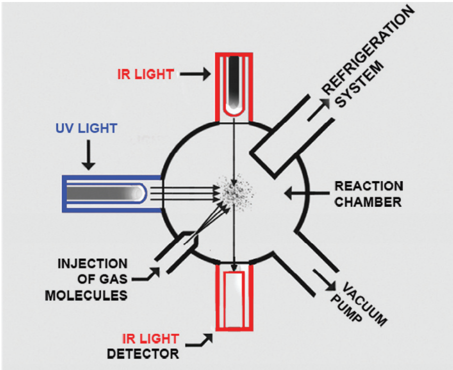


Fig. 47
Scheme of a simulator of gas and dust clouds.

It is possible to simulate in the laboratory chemical reactions that occur everywhere in the Universe where ice grains exposed to UV radiation may exist, not only in interplanetary and interstellar space but also in comets; in these reactions complex organic molecules are formed. In general, the process of simulation involves conditions of temperature, pressure and radiation representative of interstellar space (Fig. 47). The molecules thus obtained are similar to those found in meteorites and in interstellar dust particles, commonly known as IDPs.[12] Icy grains of dust containing PAHs were also simulated; it is noteworthy that 20% of the cosmic carbon is in the form of these structures. When they were subjected to UV radiation, PAHs changed into significant organic molecules such as esters, alcohols and quinones[13] (Fig. 48). The capacity of quinones to transport electrons plays an important

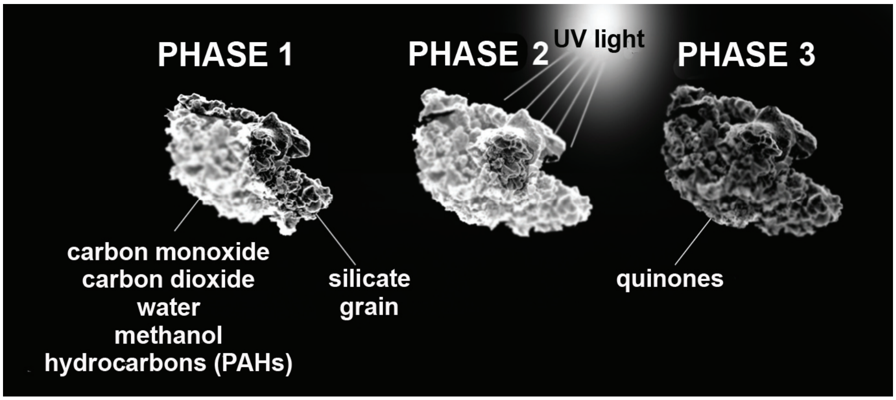
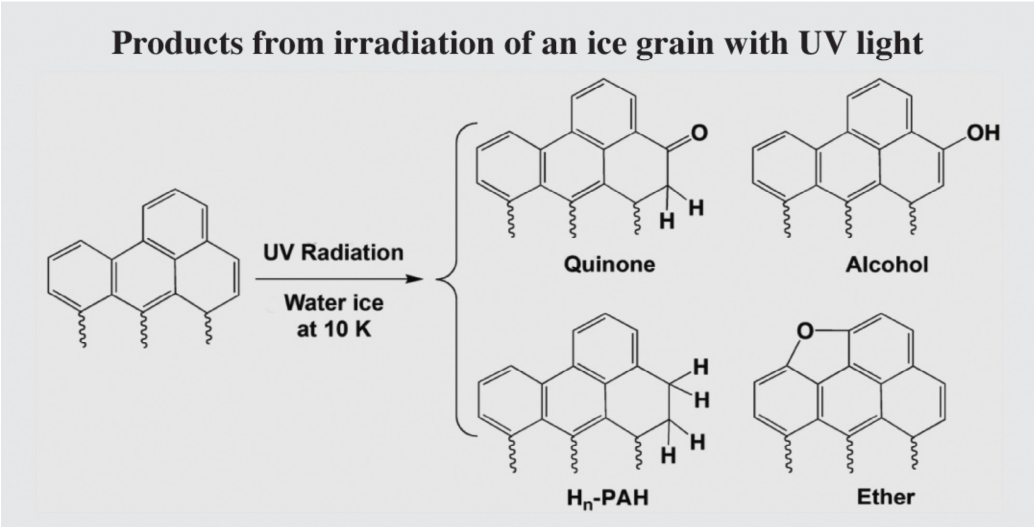


Fig. 48
Formation of complex compounds on a silicate grain in sidereal space.

12 Interstellar Dust Particles.
13 Quinones are aromatic ketones, i.e. benzoketones or ketones of benzene derivatives.



role in the conversion of sunlight into chemical energy during photosynthesis, associated on Earth with green plants. This ability of quinones is particularly relevant to the state of the early Earth before the formation of the ozone layer. In this context they would be able to absorb radiation, so acting as shields against UV radiation and protecting other key molecules such as amino acids.

Laboratory studies showed that the PAHs, produced by irradiation with UV light in aqueous medium, retain their ability to react on interstellar ice grains, either by reduction or by oxidation, and become the possible source of some hydrocarbons in carbonaceous chondrites and IDPs. By photolysis[14] with UV light of mixtures of water, formaldehyde (H_2CO), ammonia (NH_3) and methanol (CH_3OH), similar to those found in interstellar ices, NASA researchers, particularly Jason Dworkin of the Astrobiology Laboratory, and Louis Allamandola, of the Ames Research Center, obtained the amino acids alanine, glycine and serine. Their results, obtained by IR spectroscopy, suggest that these amino acids should exist and be constantly formed in space as a result of stellar photochemistry.

Many other compounds can be obtained in simulation experiments of interstellar ices; these provide important information regarding the origin of Life. In 1999, by UV radiation of a chemically simple mixture (but important in astrochemical terms) of water, methanol, ammonia and carbon monoxide, David W. Deamer of the University of California at Santa Cruz, obtained a complex mixture containing amphiphilic molecules (Fig. 49) similar to those found in the Murchison meteorite, with the property to self-organize into vesicles (Fig. 50). The cell wall of living beings, through which they

14 Cleavage of molecules by the action of light.

Amphiphilic molecules

The phospholipid phosphatidylcholine is used as a medicine to remove cellulite and is an example of an amphiphilic molecule. Part of these molecules is water-soluble (hydrophilic), containing atoms of nitrogen and/or oxygen, while the rest is insoluble in water but soluble in oils and hydrocarbons (hydrophobic), consisting of one or more chains of carbon and hydrogen atoms (mainly CH_2 groups). Soaps and detergents are formed by amphiphilic molecules, which, by dissolving their hydrophobic part in the fat in such a way as to form droplets they keep their hydrophilic part facing out; in this way, the whole droplet, and indirectly the fat, is solubilized in water.

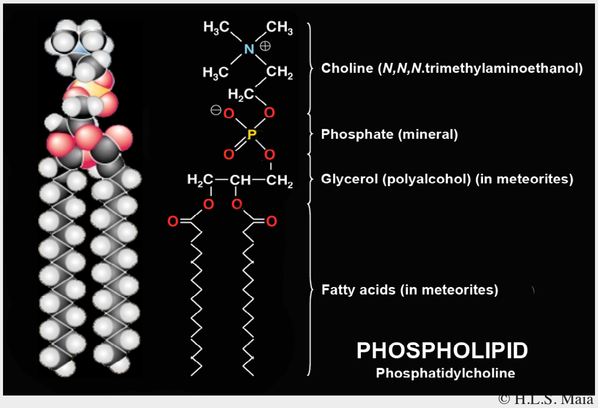


Fig. 49
Exemple of an amphiphilic molecule, the phospholipid phosphatidylcholine.

The cell membranes are formed by a bi-layer of amphiphilic molecules such as in their outer layer. These molecules have the hydrophilic part facing out, while the inner layer faces inside; the whole, so-called vesicles, are hydrophilic both inside and outside the cell, but the area of contact between the two layers is hydrophobic. In meteorites not only are the main components of these molecules (sugar and fatty acids) found but also amphiphilic molecules have been found, which organize themselves spontaneously into vesicles.

receive the food and the energy essential to Life, are similar to these vesicles both in structure and in shape. The membrane structures of the cell wall are needed to separate and protect from the outside world the chemistry involved in the Life processes. The rapid formation of these and other prebiotic molecules by irradiation of interstellar ices shows that some of the organic compounds that may have fallen onto the primitive

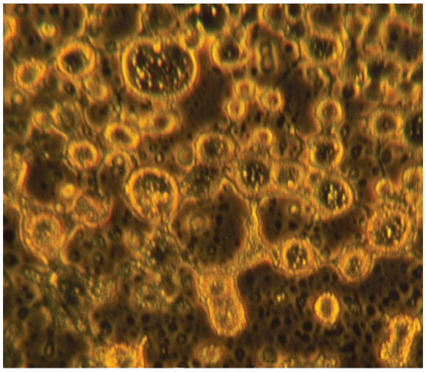


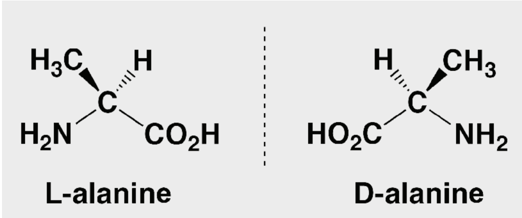
Fig. 50
Auto-organization into droplets when a mixture with a composition typical of outer space is irradiated with UV light and then dispersed in water.
Credit: NASA Astrobiology Institute.
URL: http://science.nasa.gov/headlines/y2001/ast05apr_1.htm

Earth by meteorites and interstellar dust particles, may have had their origin in cold, interstellar regions; their arrival on the Earth and on other planets of our solar system, or indeed of other solar systems, may have had an important role in the origin of Life on Earth and in the Universe.

7.3 The origin of chirality

When we put our hands palm to palm, we see that each looks as if it were a mirror image of the other; they are symmetrical with respect to each other. Many carbon compounds can generate molecules with this property, i.e. pairs of molecules that are mirror images of each other and cannot be superimposed. This includes sugars and the common amino acids with the exception of glycine. This property, known as chirality, is the result of asymmetry within molecules, most often as a consequence of the fact that each carbon atom is able to connect to four other atoms or groups of atoms in a tetrahedral arrangement; chirality occurs when the four atoms and/or groups of atoms bonded to a carbon atom are all different from each other. In the synthesis of amino acids encoded by the DNA, either by the Strecker, Miller, or any other method, each amino acid is always generated as a mixture of equal amounts of both mirror image forms; these two forms are commonly called enantiomers, one being labelled with the letter D (*dextro*) and the other with the letter L (*laevo*),[15] placed before the name of the

15 From the Latin *dextro* (right) and *laevo* (left).



amino acid (e.g. L-alanine and D-alanine, L-serine and D-serine, etc.). However, the living beings that inhabit the Earth have only amino acids of the L form and for this reason they are said to be homochiral.

When amino acids were first found in meteorites, the possibility of their being contaminated by the soil could not be ignored. When methods of chemical analysis had become sufficiently refined to distinguish between L and D forms, it was found that in all cases the amino acids existed in equal amounts of both forms, implying no soil contamination. Skeptics then argued that these amino acids were not related to Life or living beings, since the amino acids of living beings are always L. With continuing progress in scientific knowledge and in analytical methods, it became established that the L form of any amino acid of a dead species is transformed, albeit very slowly, into the corresponding D form, thus leading to an equiabundant mixture of both forms. This phenomenon, called racemization, is accelerated by light, particularly UV light, and also by high temperatures; however it is still slow enough to be used for dating the remains of moderately ancient living things. This means that if the amino acids contained in the meteorite had been generated in living beings with preference to the form L (or even to D), these compounds could reach the Earth as fully racemized species, i.e. as mixtures of equal amounts of L and D, as the racemization process had been accelerated by the intense UV radiation received en route and/or the heating caused by friction with our planet's atmosphere.

However, with further progress in analytical methods, by 1993 John R. Cronin, of the University of Arizona (USA), found that some of the amino acids that were present in both the Murchison and the Murray meteorites exhibited a slight excess of the L form, implying that this form had initially prevailed and its racemization was not complete. In these cases there is no suspicion of contamination, since the amino acids involved do not exist in living beings as they do not occur on Earth unless by laboratory synthesis. Similarly interesting is the fact that these amino acids are more resistant to racemization than those encoded by DNA. Any remaining doubt was removed when, due to progress in the mass spectrometry technique it was concluded that the amino acids analyzed contained the isotope 15 of nitrogen (^{15}N) in greater abundance than that typical of the Earth and of terrestrial amino acids. Thus, the amino acids found in meteorites appear to be truly alien and this excess of nitrogen-15 is a marker of alien compounds. Also, carbon-13 (^{13}C) and hydrogen-2 (^{2}H or ^{2}D) are found in meteorites in

excess of the percentage found in terrestrial compounds, and both are markers of amino acids, sugars and other materials received from outside the Earth.[16]

Once this issue is clarified, another question still stands, as will be seen below. When one wants to synthesize any of these amino acids in the laboratory, both enantiomers are formed simultaneously and in equal quantity, since the probability to generate one form is exactly the same as that to generate the other. This is equally true in the case of the Miller-Urey experiment, the aim of which was to establish a connection between the origin of Life and the believed characteristics of the primitive atmosphere of Earth. It is possible to induce in the laboratory an excess of one of the forms over the other, but only if for such purpose a homochiral medium is previously available as, for example, an appropriate chemical reagent (necessarily derived directly or indirectly from living organisms). Thus, the homochirality of living agents and the enantiomeric excess in meteorites appear to present a paradox and prompts the following question: how did this excess of enantiomers of L-amino acids, which all living beings use exclusively, originate in the Solar System? Here we have a real Columbus egg situation. If these two forms are produced in equal amounts, but both are likely to be destroyed by the action of light, then one of them, D, must inevitably be destroyed faster than the other. But why? Sandra Pizzarello and her co-author John Cronin suggested that the enantiomeric excess may have been caused by the action of circularly polarized UV light from a neutron star. Indeed, laboratory experiments

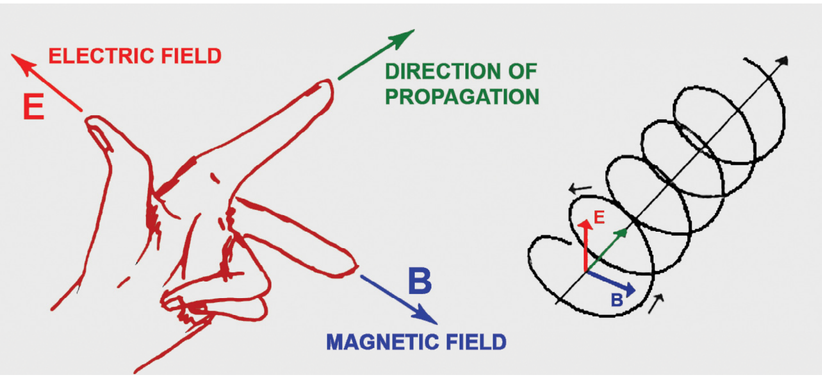


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Fig. 51
The ‘three fingers rule’ defining the orientation of the vectors ‘propagation’, ‘electric field’ and ‘magnetic field’, orthogonal to each other, according to Maxwell’s laws, and also a schematic illustration of the propagation of a beam of circularly polarized light (towards the left).

16 On Earth, the natural atomic mass of nitrogen is 14.007, corresponding to 99.3% of the isotope of mass 14 (nitrogen-14) and 0.7% of the isotope of mass 15 (nitrogen-15); similarly, the mass atom of carbon is 12.011, corresponding to 98.9% carbon-12 and 1.1% carbon-13; the mass of hydrogen is 1.008, representing 99.2% of hydrogen (hydrogen-1) and 0.8% of deuterium (hydrogen-2). Therefore, the atomic masses of these elements in chemical compounds found in meteorites are larger than 14.007, 12.011 and 1.008, respectively.

show that a racemic mixture of the amino acid leucine exposed to circularly polarized UV light is enriched in L-leucine. According to the Maxwell[17] laws (Fig. 51), light can be characterized by a system of vectors orthogonal to each other, defining the direction of propagation, and the magnetic and electric fields; this set of three vectors corresponds to a chiral system whose image in a mirror has no real existence. In circularly polarized light the electric field and magnetic field vectors rotate jointly about the propagation vector, thus defining a helical propagation. Whilst circularly polarized light can be generated in the laboratory, it has also been detected in the region of the Orion constellation, although in this case its origin is poorly known. From all our knowledge of the Universe, light is the only reality that is intrinsically chiral. The hypothesis that polarized light could itself induce an enantiomeric excess during synthesis of amino acids in the interplanetary or interstellar medium is therefore not too far-fetched a theory.

7.4 The role of comets, meteorites and micrometeorites

When our Solar System was generated, not all the material that formed the initial cloud of gas and dust coalesced to form the Sun, the planets and the planetesimals. Much of this material, mostly that further from the center, remained in a translatory equilibrium at the periphery, a region known as the Oort cloud. When this equilibrium is disturbed by any accidental cause, any of the bodies that resided there can be projected to the inner Solar System, thereby giving rise to a comet. Such a comet, now with a highly eccentric orbit, will be directed towards the inner Solar System and will repetitively visit it with a characteristic frequency. During one of such visits it may clash with one of the planets, which would then result in a catastrophic impact; however, what usually happens is a mass loss of the comet each time it appears. Comets are huge blocks of matter whose “cement” is made of water ice and chemical materials that are in the solid state at the low temperatures of the interplanetary space. Each approach to the Sun causes partial melting and disaggregation of these materials to produce the coma and the tail, the parent comet leaving these materials scattered along the path it described.

Each comet whose orbit is co-planar with the major planets of the Solar System may cross the Earth’s orbit, and this movement will repeatedly cross the regions where the cometary material had been dispersed. So, by gravitational pull, this material will be attracted to our planet, entering the atmosphere where, by friction, the larger bodies become incandescent and give rise to periodic falling stars (meteors) whenever the planet crosses a region traversed by a comet. Bodies that, due to their size, are not completely vaporized will fall to Earth in the form of meteorites (Fig. 52). The lighter materials and the smaller bodies, such as dust, do not produce the spectacle of shooting stars, as they land gently

17 James Clerk Maxwell (1831–1879).

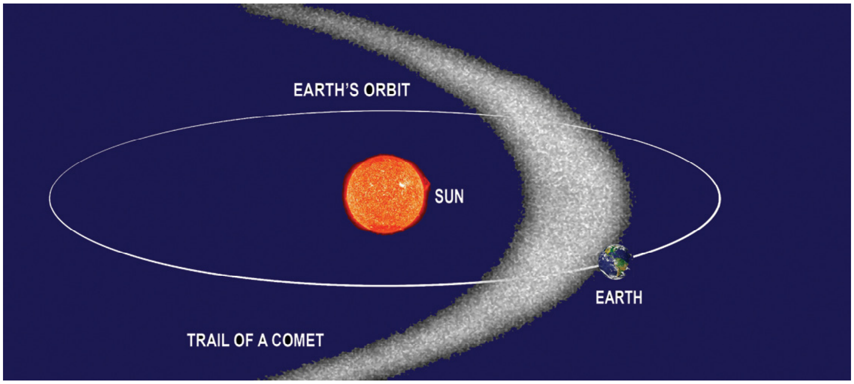

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Fig. 52
Fall of meteorites and micrometeorites originated in the tail of a comet.

without heating, thus contributing to the approximately 100 tonnes of material that on average falls each day on our planet. Naturally, as these materials are being deposited in the various planets of the Solar System, they become scarcer in their places of origin, which makes one conclude that in the past the fall of materials and even bodies from interplanetary space would have been much more frequent and significant than it is nowadays. Moreover, the many craters that can be observed on the Solar planets, Earth included, provide such evidence.

It is believed that this exogenous material may have contributed to the enrichment of the Earth and the other planets in their early stages of their formation, with a whole set of molecules essential to Life. Indeed, the interstellar ices that constitute a major part of a comet's body contains a large amount of biogenic elements. As many meteorites result from disaggregation of comets, the study of these bodies becomes important in the subject of prebiotic chemistry. Chemical analysis of meteorites belonging to the class of carbonaceous chondrites, as is the case of Murchison and Murray meteorites, revealed the existence of monomers essential to life, namely, amino acids,[18] sugars and nucleic acid bases.

Since July 1984 micrometeorites[19] have been collected in large numbers in the ice of Greenland and, in particular, in Antarctica. Most Antarctic micrometeorites belong to the class of carbonaceous chondrites as they contain high concentrations of carbon (7% carbon with respect to the overall weight), including organic material such as amino acids and PAHs. For many years, the only experimental evidence about micrometeorites was the observations made by the transmission electron microscope and the scanning electron microscope, which showed that most of these bodies were formed by clusters

18 Of the amino acids that are known to be essential for most living beings present, only eight are found in meteorites.
19 Micrometeorites are particles coming from outer space, with dimensions between 0.05 and 0.5 mm, falling incessantly on our planet, settling at the bottom of the oceans or in the polar ice caps. They are simply the smaller fragments coming from space, of the family of meteors and meteorites; therefore, they have a common origin with meteorites, believed to result from disintegration of comets or from asteroid clash.

of grains.[20] Nowadays, experimental data on the carbon chemistry of micrometeorites present a new scenario in which each of these bodies may have acted as a microscopic, "chondritic" chemical reactor. So, as soon as they come in contact with water, they generate complex organic compounds (at least amino acids), by hydrolysis of their catalytic carbonaceous components. Initially, this concept was rejected in view of the apparently rapid dilution of the reagents in water and the concomitant decrease of the reaction rate. However, this impasse was overcome with the discovery in all types of micrometeorites of thin layers of magnetite, protecting them as if they were the shells of an egg, suggesting that this material was acting as a kind of inorganic membrane, essential for maintaining the reagents concentrated and protected from the primitive atmosphere. Iron hydrides also appear to be efficient "skins" for concentrating the more complex organic compounds such as amino acids.

The recent detection of organic compounds in micrometeorites by two groups of scientists (Jeffrey Bada, of the Scripps Institution of Oceanography, and Richard Zare, of Stanford University, USA) brought further support to this scenario, indicating in particular that the synthesis of amino acids in micrometeorites, involving hydrogen cyanide as a precursor, is possible in some environments. At present, it is believed that the cometary dust released in the tails of comets has been an important vehicle for the transport of prebiotic organic material to Earth; in fact, this dust belongs to the category of the very light bodies whose impact with our planet is sufficiently soft for the material contained therein not to decompose by atmospheric friction.

Studies of the interstellar clouds, interplanetary dust, comets, meteorites and micrometeorites led to the progressive development and consolidation of the hypothesis that points to a model of exogenous chemical evolution, as opposed to the endogenous model resulting from the Urey-Miller experiment (Fig. 53, next page). It is indisputable that in interstellar space there is production of complex organic molecules from material as simple as water ice, methanol, hydrogen cyanide and ammonia. Dense molecular clouds seem to exist not only in our galaxy but also in the entire Universe, and all planetary systems appear to have been formed from this material. The knowledge obtained to date and described above suggests a link between the organic materials synthesized photochemically in the grains of cold interstellar molecular clouds and the monomers of Life brought by carbonaceous meteorites and micrometeorites. The amphiphilic properties of some of these compounds allow molecular auto-organization and may have played an important role in the formation of membrane structures necessary for the first primitive life forms. The Universe produces large quantities of organic material that could have been the motor for the origin of Life on Earth or in any planetary system under formation. Having these new findings in mind, the hypothesis of a coexistence of endogenous and exogenous models in the same evolutionary scheme is accepted in some scientific circles.

20 A typical micrometeorite with a size of about 0.1 mm is composed of millions of grains embedded in abundant carbonaceous material.

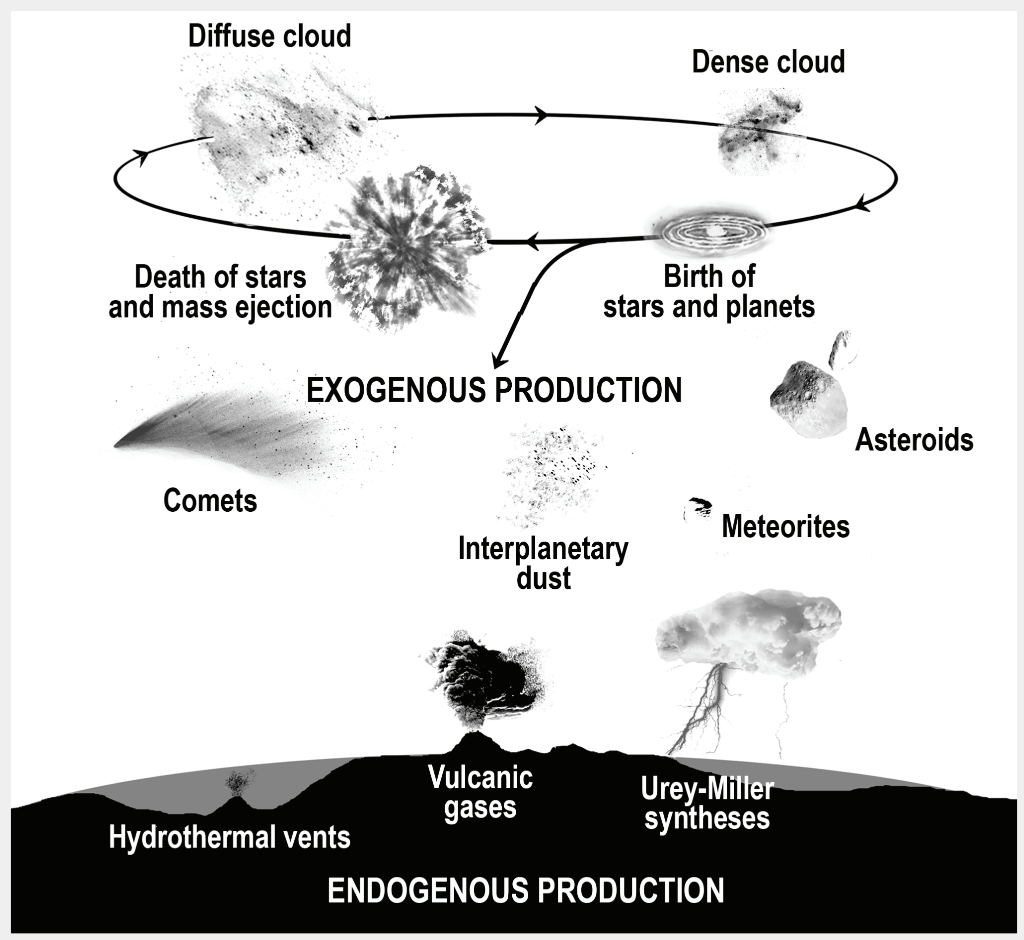

Fig. 53
Endogenous and exogenous production of prebiotic chemical material according to the concept of Jason Dworkin of NASA Ames Research Center. Endogenous production by Urey-Miller synthesis refers to the very primary stages of development of the planet; the fall of exogenous material as much as volcanic degassing have been scarcing over time.
Based on Jason Dworkin, in URL http://www.astrochem.org/LifeImplications.html

7.5 Surviving the impact

In our planet, as in other planets of the Solar System, many impact craters can be found caused by the collapse of large bodies arriving from space over a period of many millions of years after consolidation of the planet's crust. Everything indicates that these bodies should carry evolved chemical material, including amino acids, that

could have considerable significance in a supposed origin of Life on the planet. It is not immediately obvious that this chemical material could have survived the high temperatures of atmospheric entry and collision with the surface.

Regarding temperatures, a body of moderate size coming from space crosses the Earth's atmosphere in less than half a minute and, although its surface becomes very hot or even white hot, as observed in shooting stars, an organic compound inside it could survive. Indeed, in the case of a body of considerable size, its interior would remain cold; in addition, fragmentation caused by the abrupt heating would allow the cooler parts to separate before the heating of the surface reached them. Moreover, if the body reached the planet with a path almost tangential to its surface, the time of drop would be substantially increased and the speed decreased by the resistance caused by the atmosphere. In such circumstances the heat of friction would be reduced proportionately to the point of it not affecting the stability of the chemical materials being transported; however, it is uncertain whether the small number of bodies that may have reached the Earth with such a path is significant in terms of quantity of material transported.

The issue of possible damage caused by impact with the surface of the planet has been controversial for a long time amongst many experts, until Jennifer Blank and her colleagues of the University of California at Berkeley (USA) set up an experiment under the auspices of NASA to seek a plausible answer (Fig. 54). Her aim was to shoot a projectile of steel the size of a juice can to a target of metal containing a drop of water saturated with five amino acids; of these, three belonged to the twenty amino acids es-

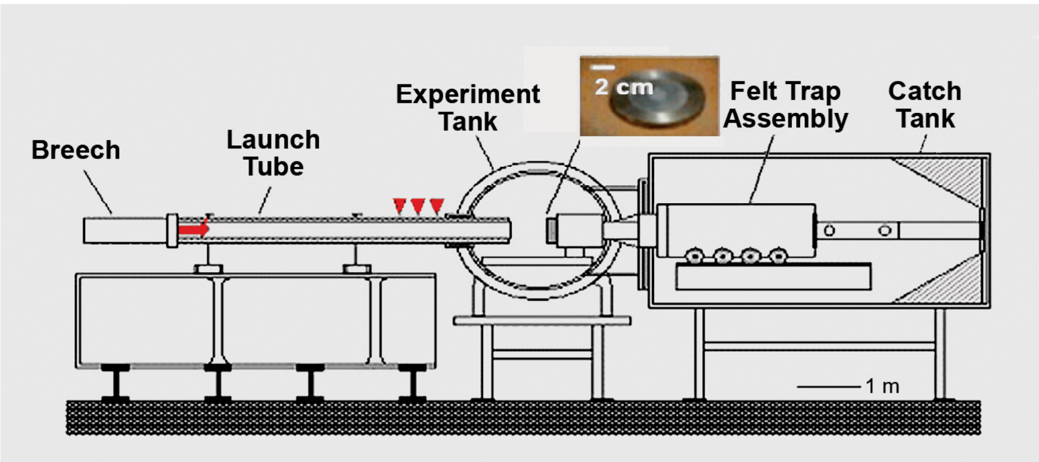

Fig. 54
Ballistic experiment with amino acids to test their resistance to impact.
Credit: Jennifer Blank, University of California at Berkeley (USA).
URL: http://science.nasa.gov/headlines/y2001/ast05apr_1.htm

sential to Life (phenylalanine, proline and lysine) and the other two were amino acids not encoded by DNA but found in the Murchison meteorite (aminobutyric acid and norvaline). The target was prepared to withstand, without breaking, a pressure exceeding two hundred thousand times the atmospheric pressure. The experiment was done repeatedly, varying the temperature, the pressure and the duration of impacts; it was found that many of the amino acids not only survived the shock but reacted with each other, forming chains with two, three and four amino acid units, (*viz*. dipeptides, tripeptides and tetrapeptides). This demonstrated that the molecules contained in falling bodies, not only resist impact but also give rise to more complex molecules in chemical reactions activated by the energy associated with the shock wave

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Chapter 8

What form of Life in the origin?

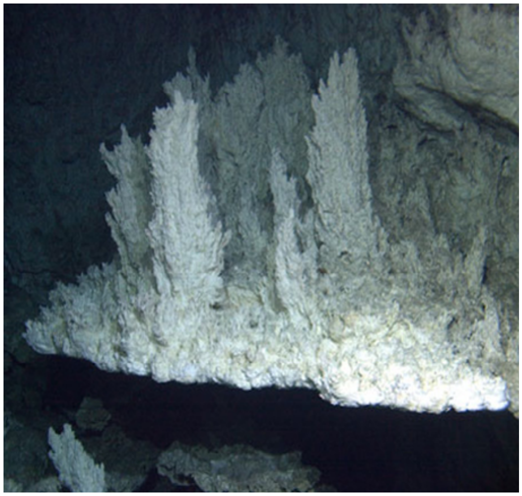

Fig. 55
Dendritic carbonate growths on the side of a chimney of "Lost City" in the Atlantic Ocean.
Credit: University of Washington / Woods Hole Oceanographic Institution.
URL: http://en.wikipedia.org/wiki/File:Lost_City_%28hydrothermal_field%2902.jpg

Science may set limits to knowledge, but should not set limits to imagination.[1]

THE DISCOVERY, IN 1977, OF POLYEXTREMOPHILE organisms that inhabit submarine hydrothermal vents, an environment reminiscent of that described by Oparin for the emergence of the first forms of Life on Earth, gave a new impetus to the endogenous hypothesis for the origin of Life. Indeed, around each hydrothermal chimney a concentric ecological system appears to develop in such a way that the apparently more primitive species are found near the vent, with more and more advanced species at increasing distances from the center. The discovery of these ecological systems led specialists to consider the possibility of Life emerging even at the present time, but this idea remains an open conjecture. However, as these extreme environments have become more understood, the information collected made it possible to detail new relationships between the extreme chemical environments of the primitive Earth

1 Bertrand Russell (1872–1970).

during the Hadean[2] period and the metabolisms that are essential for the development of living beings. This led to biochemists becoming freed from the restrictions associated with their limited knowledge of mesophile beings, and enabled them to imagine new ways of survival and to suggest new metabolic mechanisms compatible with the supposedly reducing environment that had been earlier advocated by Oparin, Haldane and Urey. But now we must refer to a medium containing sulfur that we know has always been expelled by volcanoes, and continues to be released by hydrothermal vents of the oceanic rifts. We must stress that the possibility still remains of terrestrial forms of Life being created nowadays in those almost alien environments of our own planet, but as yet we have no supporting evidence for it.

From our knowledge of the conditions of the primitive Earth and under the impetus of the discovery of extremophile microorganisms, a new stream of theories for the origin of Life has emerged during recent decades. These theories consider that the first form of Life would have been autotrophic, using carbon dioxide (or another compound of carbon) as a source of carbon and inorganic matter as a source of energy. In other words, they would be chemolithotrophic[3] anaerobic scenarios, with different researchers all proposing the possible role of sulfur compounds in the development of the first living being in a reducing medium.

8.1 The Günter Wachtershauser hypothesis

BY THE END OF THE EIGHTIES OF LAST century, Günter Wachtershauser, a chemist and patent lawyer in Munich, proposed what has become known as the "iron-sulfur world hypothesis". In this model the author believed that Life would have emerged not within the ocean waters but on the surface of iron sulfide minerals (pyrite) of the submarine hydrothermal vents. The starting material for the first organism would be carbon dioxide (or an equivalent compound of carbon, i.e. with a single atom of this element in its molecule); in order that carbon could undergo fixation, a reduction reaction would be needed. The reducing agent would have to meet certain requirements, such as being able to reduce carbon dioxide and carboxylated molecules,[4] to be geochemically plausible and have a credible relationship with the present biochemistry. Wachtershauser suggested the formation of iron pyrite (FeS_2) from ferrous ions (Fe^{2+}) existing in the Hadean ocean and from hydrogen sulfide (H_2S) provided by hydrothermal vents, as the energy source used by the first living beings. From this reaction a crystal of pyrite and an increase in the acidity of the medium would result, while the electrons needed to reduce the carbon compounds would be generated.[5]

Pyrite crystals are very stable and, as their surface is cationic, they would favor attraction of anionic carbon fixation products. In this way, a reaction would occur on the surface of the pyrite crystal, as if it were a surface metabolic system. For this proto-metabolism of

2 Definition in Chapter 1.
3 Those beings that obtain energy from oxidation of inorganic compounds of iron, sulfur, nitrogen and hydrogen.
4 Molecules having the $-CO_2^-$ group.
5 This reaction, $FeS + H_2S \rightarrow FeS_2 + 2H^+ + 2e^-$, would provide enough energy for all the other reactions involved in the metabolism, because it bears a potential of –620 mV and a Gibbs energy (ΔG^0) of –41,9 kJ mol^{-1}.

Citrate cycle

In this auto-catalyzed cycle reducing carbon fixation takes place as follows:

oxaloacetate + 2 CO_2 → citrate	(10 steps)
citrate → oxaloacetate + acetyl-CoA	(3 steps)
acetyl-CoA + 2 CO_2 → oxaloacetate	(3 steps)

oxaloacetate + 4 CO_2 → 2 oxaloacetate

At present the reaction of CO_2 fixation is catalyzed by an iron-sulfur enzyme:

$$CH_3\text{-}COSR + CO_2 \xrightarrow[\text{[Fe/S]}]{\text{TPP}} CH_3\text{-}CO\text{-}CO_2H$$

primitive carbon fixation, the author proposes a mechanism similar to the "reducing citrate cycle", but without the intervention of enzymes and in which the only reducing agent is the FeS/H_2S system (*cf*. box above). In his view, the aqueous system FeS/H_2S would be able to play three roles in this reaction: supplying enough energy, forming iron-sulfur clusters that would act as enzymes and providing the activation of the donor group of carbon by means of the formation of a thioacid (R-COSH) or thioester (R-COSR').

Later, an insufficient concentration of iron ions and/or hydrogen sulfide, would have led to the cessation of pyrite formation to obtain energy, causing the homologous citrate cycle to be also abandoned in the higher organisms (except for part of this cycle that occurs in the biosynthesis of lysine). Wachtershauser still considers that the constituents of the reductive citrate cycle are the starting point for the biosynthesis of all compounds essential to Life: lipids, sugars, amino acids, coenzymes, etc. However, in the same way as the reductive citrate cycle was abandoned, so the biosyntheses of these compounds are now thought to undergo biochemical changes in a different way.

8.2 The Russell & Hall hypothesis

In 1997, Michael J. Russell and Alan J. Hall, of the University of Glasgow, published a detailed proposal of how Life could have emerged 4.2 Gyr ago by the contact of alkaline water (pH ≈ 9) containing sulfides from a submarine hydrothermal vent at about 150 °C with acidic waters[6] of the Hadean ocean, rich in iron ions at an estimated temperature

6 The acidity was caused by a pressure of carbon dioxide in the atmosphere in equilibrium with the ocean of around 10 atmospheres. Most of this gas would result from volcanic degassing.

of 90 °C. The thermal and chemical imbalance in this interface would have given rise to the first metastable metabolism. The authors considered that in the vicinity of these sources membranes of ferrous sulfide (FeS) would have been deposited, which would act as a kind of barrier or primitive cellular membrane. These membranes would allow the presence of compounds in their interior, at a concentration different from that of the outside, in such a way as to generate small "primitive organic soups". Their idea is supported by the finding in Ireland, of colloidal formations of ferrous sulfide "bubbles" of 0.1 mm in diameter. Moreover, in experimental studies the authors were able to produce contiguous "bubbles" with approximately 0.01–0.02 mm in diameter.

Today, metabolic processes are dominated by the chemistry of carbon, hydrogen, oxygen, nitrogen and phosphorus compounds, which would have replaced the primitive iron-sulfur precipitates. However, these elements remain essential in current metabolic processes namely in the iron-sulfur proteins, generally represented by ferredoxins. The authors proposed ways by which cellular mechanisms would have evolved to originate the contemporary metabolisms. Below, we present a summary of their proposals.

Iron and sulfur

Wächtershäuser had proposed ferrous ions as a source of electrons, considering the formation of pyrite as the first metabolic step; they are in fact the largest source of electrons in the hydrothermal environment. However, pyrite is not a good iron-sulfur material for proto-metabolism in the hydrothermal context, since it has a complex structure that is very stable and difficult to reduce. So, Russell and Hall proposed the colloidal ferrous sulfide precipitates, which would form membranes spontaneously at the interface of the alkaline hydrothermal solution and the ocean waters. These membranes, such as ferrous sulfide in nature, may contain 20% of nickel, cobalt or copper. In this case, it was considered that they contain 20% of nickel, which ensures properties different from those of pyrite and allows active participation in the biochemical processes involved; this is due to the great mobility of electrons in nickel unlike in pyrite; in the Wächtershäuser hypothesis pyrite would be only a reaction product.

Subsequently, a proto-ferredoxin is proposed that has a catalytic activity supported by experimental evidence and that is able to reduce carbon dioxide, leading to formate (HCO^{2-}), oxalate ($C_2O_4^{2-}$) and carbon monoxide, a reaction catalyzed by iron-sulfur clusters, $[Fe_4S_4(SR)_4]^{2-}$, in an non-aqueous environment. The proto-ferredoxin has about 80% of the activity of the present ferredoxin. Evidence of a relationship between this mechanism and the origin of Life is provided by the fact that all present prokaryotes possess proteins with complex iron-sulfur clusters in their cell membranes. Later, other proto-ferredoxins would have formed, involving elements other than nickel, such as tungsten. In addition to those elements mentioned above, others such as cobalt, zinc and molybdenum may have been associated with organic sulfides and have had a significant role in the origin of Life.

Carbon and hydrogen

Carbon and hydrogen are chemical elements that are thought to have existed in relative abundance in the primitive ocean,[7] the former as carbon dioxide dissolved in the ocean water and the latter present in the hydrothermal solution. Probably, hydrothermal hydrogen has been the primary source of energy for emerging forms of Life. Today, the cellular processes involving carbon follow an oxidant trend. The sequence shown below with compounds that are currently involved in Life processes provides a simplified scale of energy, with hydrogen at the bottom (as an energy source, i.e. an electron donor) and oxygen at the top (as an electron acceptor),[8] all in equilibrium with water (within this series only neighboring species can co-exist):

methane→methanol→formaldehyde→acetic acid→ carbon monoxide→ carbon dioxide

It should be noted that although redox reactions are critical, they are only one example of many other types that are involved in the metabolism; equally important are polymerization, hydration and condensation reactions, not forgetting the importance of isomers.

In the absence of free oxygen, the thermodynamically stable compounds are water, carbon monoxide, methane and carbon dioxide. Reduction of the latter to other compounds, at hydrothermal temperatures below 250 ºC, has been much discussed. However, it was shown that at temperatures below 150 ºC, long chain polymers are the organic molecules produced in greater abundance and without energy costs. It will then be reasonable to assume that organic molecules would have formed by reduction of carbon oxides in a reducing hydrothermal environment. Iron sulfide membranes would receive hydrogen, acetate, sulfide, ammonia and possibly some bases from the hydrothermal fluid. The carbon dioxide coming from seawater would flow through the membranes, thus providing the composition necessary for the formation of acetyl thioester molecules, essential for the occurrence of two distinct reactions, namely hydrogenation, to produce stable fatty acids, and carboxylation and hydrogenation to produce citrate. Once produced, citrate regenerates oxaloacetate and acetyl thioester, and the auto-catalytic cycle is repeated with a positive feedback, known as the "reverse Krebs cycle", which is the result of the high pressure of carbon dioxide (Fig. 56). The membrane of ferrous sulfide, doped with nickel and possessing proto-ferredoxins, would have been responsible for the catalysis of these polymerizations.

Nitrogen

It is thought that, by degassing of the mantle, nitrogen would be present at the hydrothermal vents in the form of ammonia and could easily have crossed the walls of the primitive cells by passive diffusion in the form of ammonium ions (NH_4^+). With the

7 About 300 mmol dm^{-3}.

8 $(H_2)\ CH_4 \rightarrow CH_3OH \rightarrow CH_2O \rightarrow CH_3CO_2H \rightarrow CO \rightarrow CO_2\ (O_2)$.

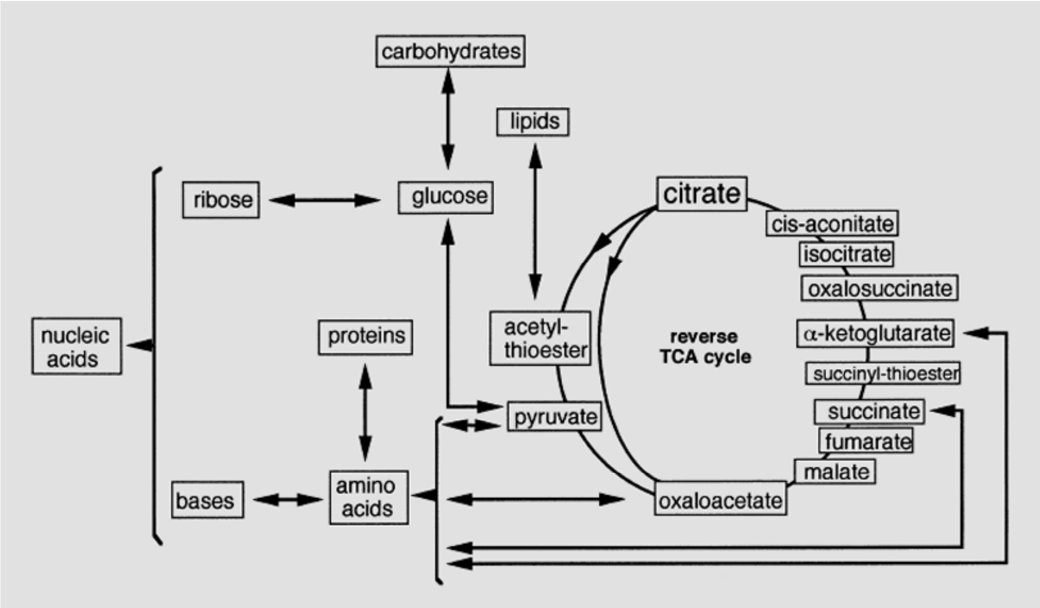

Fig. 56
Scheme of the biosynthesis based on the reverse citrate or tricarboxylic acid cycle (TCA).
Reproduced from M.J. Russell & A.J. Hall.
URL: http://www.gla.ac.uk/projects/originoflife/html/2001/pdf-files/Russell_&_Hall.pdf

likely existence of hydrogen cyanide in the hydrothermal fluids, formation of amino acids and their polymerization into small peptide chains would have been possible, an essential step for replication of these protocells of ferrous sulfide. Similarly, formation of nucleic acid bases would be possible by auto-condensation of hydrogen cyanide.

Phosphorus

Phosphorus is not very soluble in alkaline media in the presence of calcium, but may exist in the form of soluble polyphosphate ions, formed by hydrolysis of the final combustion product of phosphorus (P_4O_{10}). Diphosphates could have penetrated the membrane and, in a reaction mediated by a thioester, have generated energy by re-hydration. This is a process similar to the one that occurs with ATP when it is converted into ADP and AMP in living organisms.[9] The reaction of ATP already holds within it much organic evolution, which makes it difficult to integrate it into this early stage of the origin of Life. However, the re-dimerization of mono-phosphate could occur abiotically under the shelter provided by the membrane of

9 ATP = adenosine triphosphate, ADP = adenosine diphosphate, AMP = adenosine monophosphate. In green plants ATP is produced from ADP during photosynthesis; the ATP, being energy-rich due to its small chemical stability, takes part in various metabolisms.

ferrous sulfide, and this would separate fluids with different values of acidity whose mean value would coincide with that of the equilibrium of inorganic pyrophosphate and monophosphate.[10]

Involvement of phosphate in such a primitive metabolism could justify their presence on systems such as coenzymes, RNA and DNA. In this case, it is suggested that a conversion of a "geochemical metabolic" process into a biochemical metabolism would have occurred, catalyzed by membranes of ferrous sulfide precipitated at the interface of the hydrothermal fluid with seawater. The metabolism would not be restricted to two dimensions as in the case of Wächtershäuser's hypothesis, but occur in three dimensions, operating in a large-scale in the hydrothermal convection. The differentiation of a set of metabolic pathways starting at the hydrothermal vent and its unification with the metabolic processes of the primitive cell probably may have arisen at a later stage, together with RNA/DNA. The prevalence of organic molecules would have come later, with the synthesis of fatty acids and complex molecules involving nitrogen and sulfur inside the chambers of ferrous sulfide, which gradually became more complex and stable, until they became independent of the primitive inorganic membranes.

8.3 The Cody *et al*. hypothesis

In 2004 G.D. Cody and his colleagues, from the Carnegie Institution of Washington, although not proposing a concrete hypothesis for the origin of Life, published results of a series of tests with various sulfides of metals such as nickel, cobalt, iron, copper and zinc, to identify which of them would best promote a model of carbon fixation that would be appropriate to the reducing environment of the early Earth. This investigation consisted in testing the formation of a carboxylic acid by hydro-carboxylation (Koch reaction) by insertion of a carbonyl group into an alkyl group bonded to the metal sulfide. The experiments were conducted at high concentrations of reagents and at high pressure (2000 atmospheres), to facilitate the action of the reagents, and also at high temperature (250 ºC). The substrate used was nonanthiol and the source of carbonyl groups was formic acid in aqueous solution; the reaction products were decanoic acid and hydrogen sulfide.[11] The reactors were small tubes of gold, so that the reactions that might occur on the surface would not intervene in the final result. Based on the experimental results, it was concluded that:

- The reactions are catalyzed by the surface, which is consistent with the occurrence of the same in a primitive environment and at low concentrations.

- With the exception of copper sulfide (CuS), all the metal derivatives studied promoted hydro-carboxylation, the nickel sulfides (NiS and Ni_3S_2) and cobalt sulfide (CoS_2) being particularly effective.

10 $2HPO_4^{2-} + H^+ \rightarrow HP_2O_7^{3-} + H_2O$.

11 $CH_3(CH_2)_8SH + CO + H_2O \rightarrow CH_3(CH_2)_8CO_2H + H_2S$.

- The number of sulfides that occur in nature is far greater than those the authors tested, so the results show the abundance of mineral catalysts that may have been useful in the origin of Life. Therefore, it is suggested that it might not be necessary to determine a “special” composition of a particular mineral that may have promoted the reactions essential to the origin of the first organism. The challenge remains to determine the involvement of each catalyst in each of the reactions, as well as determining when and how the prebiotic chemistry resulted in the emergence of Life.

8.4 Chemolithotrophic organisms — Biogeochemical cycles

As previously stated, the existing models for the origin of Life are based on inferences drawn from the study of present life forms that grow in inhospitable environments, similar to those that have existed on early Earth; this approach was adopted in an attempt to explain how their biochemistry has evolved from a prebiotic chemistry. At this point, a brief review of the current anaerobic chemolithotrophic metabolisms that could be used as models for studying the origin of Life will be presented, together with a summary of the biogeochemical cycles of certain chemical elements with which those organisms are involved and that are of great importance to the ecosystems.

Nitrogen

Inorganic nitrogen compounds are very common as electron acceptors in anaerobic respiration (Fig. 57). The most common species of nitrogen in Nature are ammonia, nitrate

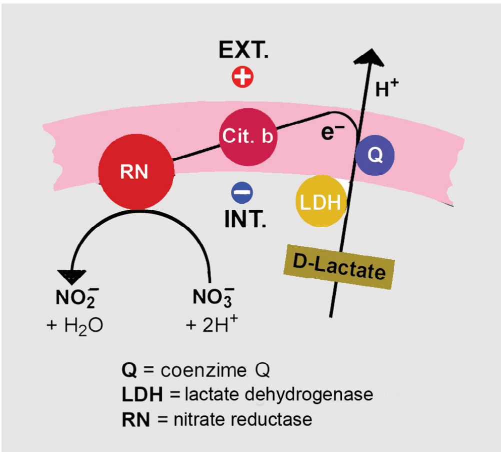

Fig. 57
Electron transport process in *Escherichia coli*; NO_3^- is used as the electron acceptor.

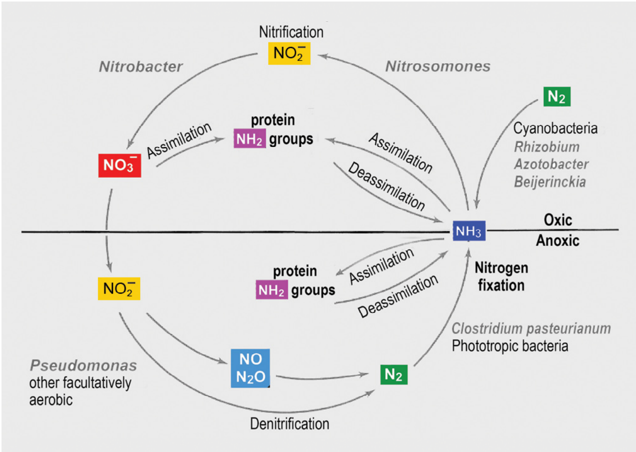

Fig. 58
Redox cycle of nitrogen in Nature.

ions and molecular nitrogen. Nitrate (NO_3^-) is reduced to nitrous oxide (N_2O), nitric oxide (NO) and molecular nitrogen (N_2). As these are gaseous products, they can easily be lost; so this process is called denitrification. The dissimilatory reduction of nitrate can terminate in molecular nitrogen or ammonia. These reductions can also occur from nitrite (NO_2^-).

The biochemical reduction of nitrate has been studied in great detail in *Escherichia coli*, an organism that, by using cytochrome–b as a source of electrons, reduces nitrate only to nitrite by means of an enzyme called nitrate reductase that is linked to its cell membrane. Nitrate-reducing bacteria have been discovered in hydrothermal vents, in environments that are believed to have existed on the prebiotic Earth. For example, the *Caminibacter mediatlanticus* sp. nov. TB–2^T was discovered in a hydrothermal vent located on the Atlantic Rift, at a depth of 2305 meters; after insulation it was found that it could use nitrate as effectively as sulfur as an electron acceptor. These bacteria, together with nitrifying bacteria that fix atmospheric nitrogen, play an important role in the biogeochemical nitrogen cycle, since it is carried out almost exclusively by these microorganisms (Fig. 58).

Sulfur

Transformations of sulfur are even more complex than those of nitrogen, due to various possible oxidation states and also because some of these changes occur both chemically and biologically. However, its more common oxidation states in Nature are –2 (R-SH and HS^-), 0 (elemental sulfur, S) and +6 (SO_4^{2-}). The state in which sulfur is found depends on the pH of the medium; at a low pH, the preferred species is hydrogen sulfide (H_2S); at the neutral pH, it is bisulfide (HS^-); and at high pH, it is the sulfide ion (S^{2-}). The sulfate ion, very abundant in seawater, is used as electron acceptor in the metabolism of sulfate-reducing bacteria (Fig. 59).

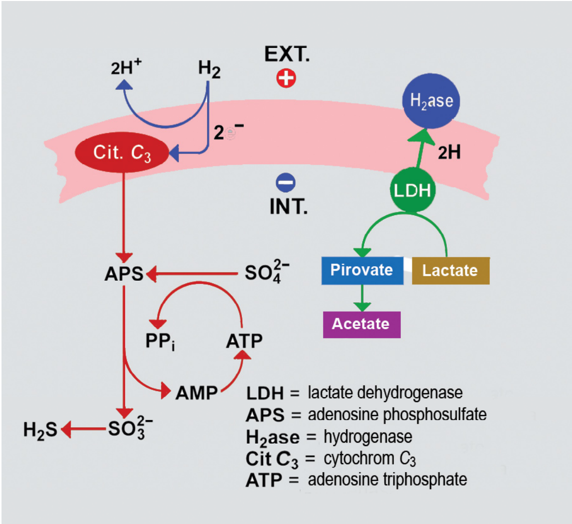

Fig. 59
Transport of electrons in a sulfate-reducing bacteria.

These bacteria may use different electron donors. The product of these reactions is hydrogen sulfide, a biogeochemically most important molecule. Sulfate is an electron acceptor much less favorable than oxygen or nitrate; thus, the growth rate of these organisms is relatively small. The sulfate ion is very stable, requiring its activation by ATP to form adenosine phosphosulfate (APS); only then is it reduced.

The reductions and oxidations of the biogeochemical cycle of sulfur involve a wide variety of organisms. New species of sulfate-reducing bacteria have been discovered in high temperature marine environments (hydrothermal vents and marine explorations of oil), as *Thermodesulfobacterium hydrogeniphilum* sp. nov. SL6T, discovered at a hydrothermal vent in Guaymas Basin, Gulf of California.

Carbon

Carbon dioxide is very common in Nature and is a product of the metabolism of chemoorganotrophic organisms.[12] Some groups of prokaryotic organisms use it as an electron acceptor in anaerobic respiration. Among those organisms methanogens, which use hydrogen as the electron donor, producing methane and water, stand out. From the same reagents the homoacetogenic organisms produce acetate and water as their sole metabolism end products.

In the carbon biogeochemical cycle, one should stress the importance not only of the photosynthetic organisms, which convert carbon dioxide into oxygen and sugars, but also

12 They obtain energy from oxidation of organic compounds.

the importance of those that decompose organic matter to produce carbon dioxide again.

Some microorganisms reduce the ferric ion (Fe^{3+}) to ferrous ion (Fe^{2+}), which is a form of anaerobic respiration. The reducing potential of the pair Fe^{3+}/Fe^{2+} is very high; so, the reduction of iron can occur in conjunction with the oxidation of a series of electron donors, both organic and inorganic. Iron is one of the most abundant elements in the Earth's crust, its cycle being related at certain points to the sulfur cycle, because some bacteria can reduce ferric ion to ferrous sulfide (FeS). This is, in fact, the metabolism proposed by Russell and Hall for the first forms of Life that emerged on Earth.

8.5 Symbiogenesis

In 1867, the Swiss botanist Simon Schwendener (1829–1919) claimed that lichens are organisms consisting of an alga and a fungus, and in 1879 the German botanist Anton de Bary (1831–1888) introduced the concept of symbiosis (from the Greek *sym*, "with" and *biosis*, "living") to explain these associations of two different life forms to their mutual benefit. At the same time the elements of any growing society differentiate their functions, cooperating with others for the common welfare in a spontaneous self-organizing process. The societies in which humans live, even the most primitive, have symbiotic characteristics; the same can be said with regard to ecological systems. The digestive system of a multicellular higher being is inhabited by microorganisms performing functions that are essential to the life of the host, this consisting, for all practical purposes, of two different sets of cells: those that are part of their tissues and the micro-organisms that cooperate with the former. By the same token, a living being is a multicellular differentiated system that is self-organized from the starting cell (egg) with the formation of a "society" prepared to resist aggression from the external environment. But each cell is made up of several parts and many complex chemical compounds, each one designed to accomplish, differentially and in a collaborative process, each of the tasks that are essential to their survival and to that of their species.

In 1909, the Russian biologist Konstantin Merezhkowsky (1855–1921) developed the concept of symbiogenesis to characterize the origin of new organisms by the possible combination or association of two or more beings who are living in symbiosis, particularly if this combination allows them to better resist extreme and adverse environmental conditions. In this work, Merezhkowsky discussed the origin of chloroplasts and of the nucleus in eukaryotic cells. He argued that the chloroplasts[13] have resulted in free-living cyanobacteria that, having colonized primitive cells, evolved as symbionts. The nucleus would represent a colony of bacteria living in symbiosis with another organism composed of protoplasm.[14] This biologist also pointed out that the first living beings would have been able to survive in

13 Corpuscles (organelles) found in plant cells and algae, which are rich in chlorophyll and are responsible for their green color.

14 All that is found inside a living cell.

Fig. 60
From left to right: Konstantin Merezhkovsky, Lynn A. Margulis and Freeman J. Dyson.
Photos: Lynn Margulis by Javier Pedreira and Freeman Dyson by Jacob Appelbaum.

extreme environments on early Earth. It is noteworthy that, in the same country and within only two decades, two scientists, Merezhkowsky and Oparin, independently developed concepts of fundamental importance to our present knowledge of the origin and evolutionary development of the first living organisms; although such concepts are now outdated, much of our modern knowledge about our origins stems from their work.

The idea that symbiotic phenomena gave rise to eukaryotic cells was revived in 1967 by Lynn Alexander Margulis (1938–), of Boston University, with her sequential endosymbiotic theory. This theory proposes that membrane organelles[15] such as chloroplasts and mitochondria,[16] have resulted from free-living prokaryotic cells (cyanobacteria and bacteria), and that the eukaryotic cell should be seen as the result of the evolution of primitive symbioses (Fig. 61). As early as 1983, based on the ideas of Lynn Margulis, Freeman J. Dyson (1923–), of the Institute for Advanced Study, Princeton (USA), presented a hypothesis for the origin of Life using symbiogenic concepts. He proposed that the prebiotic evolution should, on the one hand, have occurred through independent formation of the metabolic systems and, on the other hand, by self-replicating molecules. At one point, some of these molecules would have been embedded in several of these systems, interacting with them at first as parasites but later as symbionts. Any variation in the genetic molecules favorable to the symbiotic system created would have been preserved over time, thus allowing evolution to occur.

According to theories, living beings when considered as symbioms, are real super-organisms incorporating not only their chromosomal genes and organelles but also bacterial symbionts and even viruses. Today, some authors, among them Jan Sapp, of York University (Toronto, Canada), believe that macro-evolutionary changes may have

15 Each of the corpuscles existing in the cells of living organisms.
16 These are the parts (organelles) of the cells of living organisms that are responsible for phenomena associated with respiration (acquisition of energy).

resulted from physiological and genetic integration of the taxonomic groups, particularly in the case of eukaryotes and even higher living beings. Recent advances in the techniques used in the field of sequential genomic analysis have provided much fundamental information for understanding evolutionary phenomena. In fact, it was possible to verify the existence of frequent exchange of genes between different bacterial species, which came to disturb the microbial phylogeny, one of the areas of science most affected by the results of nucleotide analysis. However, again according to Jan Sapp, these results, from the point of view of symbiosis, seem to contradict the principles underpinning neo-Darwinian theory.

The combined action of proteins with nucleic acids for registration and use of information in living things is, to our eyes, a kind of symbiotic association. In fact, independent of the possibility of the compounds of each class being able to perform both functions for better or worse, it is in this cooperative association that truly highlights their performance. In the same way, systems capable of both chemical and biochemical autocatalysis may be viewed as cooperative. It is very likely that well before the perfect interconnection found today between proteins and nucleic acids was reached, complex chemical systems consisting of prebiotic material may have interconnected cooperatively in self-organizing ways, and thus act as real precursors of the fundamental mechanisms that are currently recognized as essential to living beings as we know them.

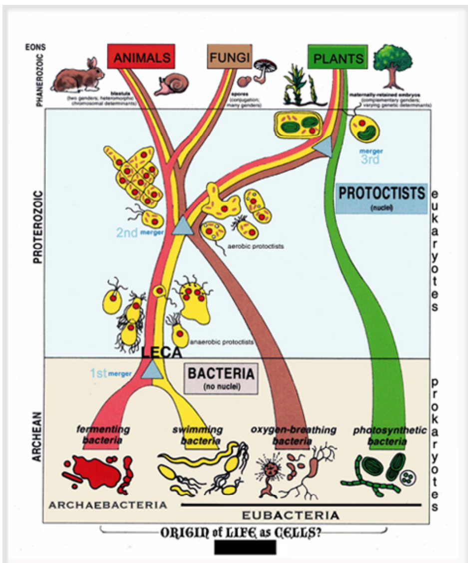

Fig. 61
Schematic representation of endosymbiogenesis.
Courtesy of Professor Lynn Margulis, University of Massachusetts, Amherst, USA.
URL: http://www.chelseagreen.com/bookstore/item/mind_life_and_universe:paperback/associated_articles

Chapter 9

Life at the time of the Earth's origin

It is difficult to say what is impossible, for the dream of yesterday is the hope of today and the reality of tomorrow.[1]

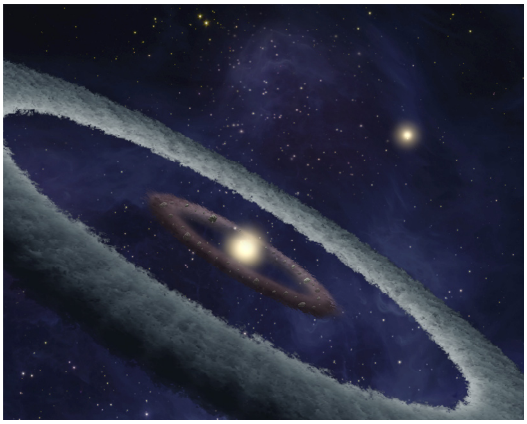

Fig. 62
Planetary system about to be formed at 424 light years from us.
Credit: NASA / JPL-Caltech / C. Lisse.
URL: http://ipac.jpl.nasa.gov/media_images/sig07-019.jpg

MANY HAVE BEEN THE AUTHORS WHO played a fundamental role in the development of Exobiology as a science. Particularly noteworthy is the pioneering work of Oparin, Haldane and Urey/Miller, who clearly laid the scientific basis for understanding the formation of organic compounds under abiotic conditions. This first stage was essential to overcome the barrier of skepticism and doubt about the possible formation of prebiotic organic compounds essential to Life in the absence of living organisms. It was mainly thanks to experimentation that this stage could be overcome, introducing new challenges and raising new questions. The Urey-Miller experiment represented a turning point in the experimental approach to the problem of the origin of Life because it involved re-creating the conditions for "spontaneous generation" of biologically significant organic molecules. By demonstrating the possibility of simulating in the laboratory the conditions supposedly existing in the early Earth, Miller opened the way to look, through experimentation, for clues on how a prebiotic evolution may have occurred, launching at the same time the bases of a new scientific discipline, Prebiotic Chemistry.

1 Robert Hutchings Goddard (1882–1945), specialist on rocket technology, June 1904.

Following this experiment, the attitude towards such a controversial and even profane subject as the origin of Life in the absence of any divine intervention, ceased to be a sacrilegious issue for some or the subject of mockery for others, but maintaining a good dose of skepticism for many. In 1957, four years after the publication of the Urey-Miller experiment the first International Conference on the Origin of Life (ICOL) took place in Russia, which was followed by other meetings under the same name in the U.S. (1963) and France (1970). Here it was decided to create a scientific society, named International Society for the Study of the Origin of Life (ISSOL). In 1973 the first congress under the auspices of the new society took place in Spain (Barcelona) and the second was in Japan (Kyoto, 1977), followed by Israel (Jerusalem, 1980), Germany (Mainz, 1983) and later in other countries, generally every three years. In 1968 a journal was released with the titled "Space Life Science", which in 1974 began to be published under the auspices of ISSOL with the new title "Origins of Life"; recently, its name was changed into "Origins of Life and Evolution of Biosphere" and is published by Springer Netherlands. Today, ISSOL has over 500 members distributed throughout 30 different countries, in which about half are U.S. citizens who are directly or indirectly connected with NASA, while many Europeans are related to the ESA (European Space Agency).

9.1 Origin and evolution

Discovery consists of seeing what everyone has seen and thinking what nobody has thought.[2]

Fig. 63
Physical map of the supercontinent Pangea.
Credit: David 'Dropzink'.
URL: http://commons.wikimedia.org/wiki/File:Pangaea_%28230_million_years_ago%29.png

As it became certain that the amino acids found in meteorites are of extraterrestrial origin, no longer was it necessary to simulate the Earth's early atmosphere to explain the formation of those compounds. So, the Urey-Miller experiment lost supporters and to many it became

2 A. Szent-Gyorgyi (1893–1986), Nobel Prize for Physiology or Medicine in 1937.

part of history, but without losing its historical and even philosophical significance; in fact, it won universal value while offering an explanation for the origin of meteorite amino acids, but outside the context of our planet.

Moreover, Oparin-Haldane's hypothesis and any experiments based on it, including that of Urey-Miller, no longer have the impact they have had, as they are based on a composition of the early atmosphere that is no longer accepted. It is thought that the atmosphere would not have been as reducing as was then imagined, but otherwise composed of water, carbon monoxide, carbon dioxide, nitrogen, hydrogen sulfide, methane, ammonia and traces of hydrogen. Another criticism of this model, though debatable, is related to the absence of oxygen in the primitive atmosphere, which would result in the absence of an ozone layer to prevent the very energetic UV radiation reaching the Earth's surface; as a consequence, the amino acids and other sensitive materials could easily be destroyed. Furthermore, the idea of a "primordial soup" is also questioned because, owing to thermodynamic criteria, accumulation of these compounds in the oceans could not have reached high concentrations as many of them would have been insufficiently stable.

The hypothesis that Oparin's coacervates have been associated with the origin of a primitive cell membrane is now refuted, not only because they are unstable structures that would not have existed for long in the primitive environment, but also because they are made of materials originating in today's living species. So called Fox microspheres are also the object of much criticism; the formation of these aggregates has only one interesting feature, namely the spontaneous auto-organization of the materials involved. At present, the phenomena related to formation of mono- or bi-layers are well studied and explained by the properties of amphiphilic molecules, which give them the ability to organize themselves according to the characteristics of the environment in which they are placed. This is a most important issue, since auto-organization is recognized as being fundamental to the emergence of molecules essential to Life — in addition to the fact that cell membranes of living beings are bi-layers of amphiphilic molecules, akin to those found in meteorites and in experiments simulating clouds of gas and dust located throughout the confines of our galaxy.

Another attempt to explain the origin of Life emerged with the formulation of the hypothesis of the RNA World. It is now generally accepted by the scientific community that RNA must have arisen before DNA, implying that the latter resulted from a development of the former. RNA is less stable than the DNA; therefore, it is an unreliable system to perform a task as important as recording and preserving genetic information capable of being transmitted between generations, an indispensable attribute for Life to reach its present degree of sophistication. While the sugar units that participate in the composition of RNA are composed of atoms, whose number is a multiple of the prebiotic and abundant formaldehyde, this does not occur with DNA, where a hydrogen atom is missing in each sugar unit; thus, DNA appears as if it were a "happy mutant" of RNA. Furthermore, today only the most elementary forms of Life do not require DNA. But, as already mentioned, the main problem of the RNA World hypothesis relates to the fact that we still have no knowledge of the mechanisms by which this molecule or its precursor has arisen from the prebiotic media.

Despite its apparent simplicity compared to DNA, the RNA molecule is already too complex for it to have emerged suddenly, ready to operate at the dawn of the processes of Life. Clearly there is a missing link that needs to be found in order to understand how Life may have emerged. At a certain stage of the evolutionary process leading up to the first living organism, a sufficiently advanced state of organization in the chemical environment must have occurred so that RNA may have arisen.

By proposing that the Earth would have been colonized by alien material, Panspermia does not answer the essential question. To its proponents, this theory has the advantage of not being falsifiable and of nurturing intellectual speculation and even science fiction. However, to the initial question as to precisely how Life has emerged, it only gives an answer for the case of the Earth, as it moves the essence of our question to elsewhere in the Universe. The initial problem therefore remains: how has Life emerged on Earth, or on any other planet or place of the Universe?

In the context of Biology, Darwinism deserves its priority because of its great impact although it continues to be the object of criticism and to feed many controversies. To summarize the whole debate Darwin's theory has generated, we can do no better than quote the following statement by Ernst Mayr (1904–2005): "I've found in the literature that there are seven or eight different meanings of the word Darwinism for different people. In Darwin's own time, for instance, Darwinism meant evolution without supernatural causation — nothing more, nothing less. Today, Darwinism means the theory of natural selection". The truth is that Evolution and its explanatory models continue to cause endless debate and cause some disunity amongst the scientific community. For the defenders of Darwinism, this is not a simple theory that can be considered true or false, but rather a very complex program of research that undergoes continuous modification and improvement. All attacks on Darwin's theory have resulted in its strengthening, since the current controversy always takes place within a Darwinian conceptual field. To critics, Darwinism seeks to find a single mechanism (not divine intervention) that would have been the generator of the past and present diversity of living beings. Accepting and incorporating the unquestionable fact that such diversity has taken different forms throughout the history of Earth, it comes up with an "explanation" that, while seeming to explain everything, explains only a little and, while providing a powerful interpretation regarding gradual evolution of species, it fails to explain the creation of new species.

The Synthetic Theory of Evolution (STE) continues to enjoy great importance, even with all the criticism that may be directed at it. This theory is a kind of very broad "biological philosophy", which provides major impetus for research in Embryology, Genetics and Ethology, amongst other sciences. But from an epistemological point of view, it is, so to speak, a theory in unstable equilibrium. On the basis of the STE, many facts are explained, but difficulties remain. These difficulties are fruitful fields of work, leading to the emergence of other theories and enrichment of scientific debate. However, Lamarckism is regaining ground, particularly with new data from the decoding of the genomes. But, some biographers say that Darwin was himself a Lamarckian, as he seemed to believe in the inheritance of acquired characteristics in connection with the variation in domestic species...

9.2 Limits to Life

That is the essence of science: ask an impertinent question, and you are on the way to a pertinent answer.[3]

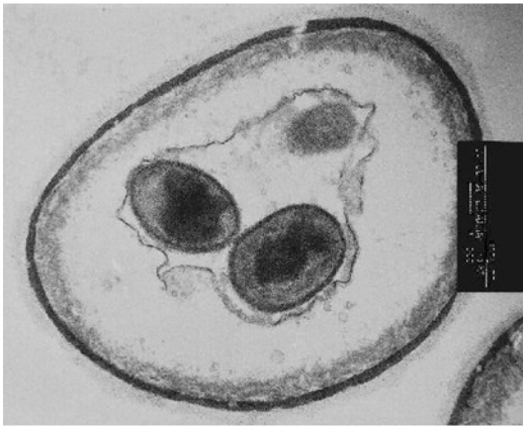

Fig. 64
Microscopic object similar to a cell of a living being collected in 2001 in southern India during a fall of red rain.
Courtesy of Professor C. Wickramasinghe,
Cardiff Centre for Astrobiology, Cardiff University, UK.
URL: http://www.astrobiology.cf.ac.uk/redrain.html

As stated above, Life must have arisen on Earth in the lower Archean eon, i.e. at about 3,5–3,8 Gyr ago. It is thought that at that time our planet had a very thin atmosphere, composed of toxic gases due to intense volcanic activity and subject to the constant bombardment by meteorites; in turn, owing to the high rate of radioactive decay its present temperature is much lower than it was in the beginning. Until very recently it was believed that, with rare exceptions, Life was only possible under the said "normal" conditions, those in which the life of higher animals develops, i.e. acidity close to neutral (pH ≈ 7), temperatures around 37 ºC, ionic strength similar to that of our blood pressure, a pressure of one atmosphere, the presence of oxygen and absence of radiation. The discovery of microorganisms capable of destroying this 'belief', and able not only to live but to grow and multiply in circumstances hitherto supposedly not allowed, has shown that Life can exist far away from solar energy and in environments very different from those thought to be necessary for biological evolution. In a scenario so harsh as that described above for the Earth at the time of the oldest fossils, it is reasonable to assume that the Life forms that arose were similar to the thermophiles or hyperthermophiles, since otherwise they would be unable to survive in such media. Thus, it is not by chance that a large proportion of Archean

3 Jacob Bronowski (1908–1974), English mathematician of Polish origin, author of "The Ascent of Man", BBC, 1973.

microorganisms are extremophiles or hyperextremophiles and that the thermophiles and hyperthermophiles are located at the base of the Tree of Life. Despite the fact that this discovery, and especially that of hyperextremophiles, has raised a particular interest in several areas for their potential economic value, Astrobiology has always given special attention to them, as they allow one to explore the limits of Life and the chances of its being found outside the Earth.

9.3 The threshold of Life

The most exciting phrase to hear in science, the one that heralds new discoveries, is not 'Eureka!' but 'That's funny!'.[4]

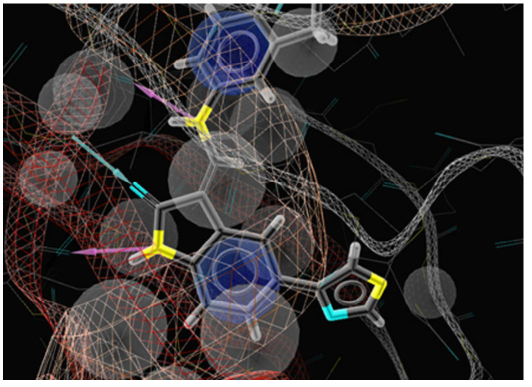

Fig. 65
Computational model of the center of a biologically active macromolecule
generated with LigandScout
(available from 'Inte:Ligand', www.inteligand.com).
URL: http://www.inteligand.com/ligandscout/manual/img/activesite.png

The latest models that support the origin of Life under reductive conditions, from metabolisms based on inorganic compounds present in extremely inhospitable environments (deep oceans at high pressures and temperatures, high acidity and lack of sunlight) are fairly consistent with the current knowledge about the conditions of the early Earth. They also go beyond some of the criticisms raised by the Urey-Miller model — for example, sunlight does not reach the bottom of the ocean, avoiding the risk of decomposition of organic molecules by the action of UV radiation. Obviously, these models have their limitations and become subjects of criticism. The main objections are related to the fact that many important biomolecules, such as aminated and phosphorylated sugars, peptides, polyphosphates and thioesters, are thermally

4 Isaac Asimov (1920–1992), biochemist and American writer of Russian origin.

unstable and, thus, would not exist for a long time under the hydrothermal conditions. Some of the key compounds proposed by Miller as precursors of nucleic acid bases would be rapidly hydrolyzed to carboxylic acids. Thus, evolution towards an RNA World would also be unlikely under these conditions.

Russell and Hall's model also has some specific limitations, as mentioned by the authors, as for example, the need for a concentration of iron (ferrous, Fe^{2+}) and bisulfide (HS^-) higher than that found in hydrothermal solutions, for the precipitation of ferrous sulfide (FeS) membranes to occur. The concentration of simple organic molecules in hydrothermal waters is lower than that required for the experimental synthesis of more complex molecules, thus preventing the formation of such molecules. The authors argued that the compartments in the membranes could serve to concentrate these molecules in their interior, but there is no conclusive evidence that this could have happened.

Currently, the most promising way to understand what is the essence of a living being is the theory of symbiogenesis, which proposes that the eukaryotic cell has been formed by successive fusions of prokaryotic cells by symbiosis. The traditional view concerning the structure and function of organisms has been conceptually changed with the progressive deepening of the concept of the symbiome. Under the symbiogenic perspective of the above mentioned authors, every plant and every animal should be considered a "super-organism", a symbiome, which includes the genes existing in their own chromosomes, the genes of cellular organelles (mitochondria and/or chloroplasts) and the genetic information of symbiotic bacteria and viruses that live in the body.

By definition, a symbiosis is an association of two different living beings with mutual benefit. It is admitted that the current eukaryotes (animals, plants and fungi) have evolved from repeated endosymbiosis between more primitive prokaryotic cells. Subsequently, these new cells would have aggregated to form multicellular organisms like ourselves. This would have occurred naturally millions of years ago. Symbiosis of various kinds would have led to the formation of the nucleus (where the genetic material, DNA, exists), of cellular organelles such as mitochondria (essential for our cells to obtain the energy needed for their operation) and chloroplasts (enclosures existing in plants and algae that allow them to use sunlight to manufacture their own food). The chemist searches for the basic chemical components that later, in a symbiotic system, may give rise to the living being we know today, while Biology tries to gradually revert back in the evolutionary chain to understand the true nature of a primitive living organism. The knowledge provided by the disciplines of Computational Chemistry and Macromolecular Chemistry on the behavior of complex molecular systems in the context of molecular auto-organization and cooperation, is being extended and improved.

9.4 History does not repeat itself!

For four-fifths of our history, our planet was populated by pond scum.[5]

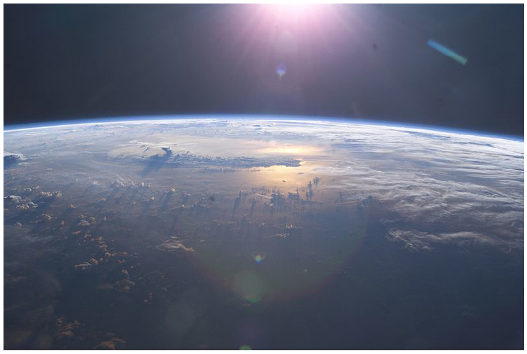

Fig. 66
Sunset observed from the International Space Station.
Credit: NASA-ISS.
URL: http://commons.wikimedia.org/wiki/Image:Iss007e10807.jpg

IT IS COMMON TO HEAR PEOPLE ASKING whether, if Life originated on Earth again or in some other place in the Universe, the resulting living beings would be in some way similar to those we know. We are not referring to aliens with an eye on the forehead or some physical shape that would identify them as aliens, as imagined by authors of science fiction. The question has a much deeper sense, in that it focuses on the biology and chemistry of such forms of Life. With the certainty that all forms of Life must be based on the known chemical elements of Nature, this is where we must begin our attempt to respond. As chance events are governed by probabilistic rules, one must conclude that all forms of Life will be composed of the most abundant elements in the Universe, starting with the most abundant element, hydrogen, followed by oxygen, carbon and nitrogen, the so-called biogenic elements; at this level the Universe is completely deterministic (Fig. 67). Magnesium, silicon and aluminum, the so called refractory elements, follow the abundance order. Although they may participate in some metabolisms of the known living organisms, they are quite secondary as compared to the biogenic elements. They might have more influence on forms of Life emerging in environments at temperatures significantly higher than those mentioned above, particularly in the case of silicon. Then, there are the influences of the elements sulfur and iron in ferredoxins and in the presumed primary metabolism proposed by Wächtershäuser, sodium in physiological saline and in many essential metabolisms, phosphorus in nucleic acids (DNA and RNA) and in ATP/ADP/AMP, and calcium in the bones and shells. All such elements are important for the many forms of Life we know.

5 J. William Schopf, professor of paleobiology at the University of California at Los Angeles.

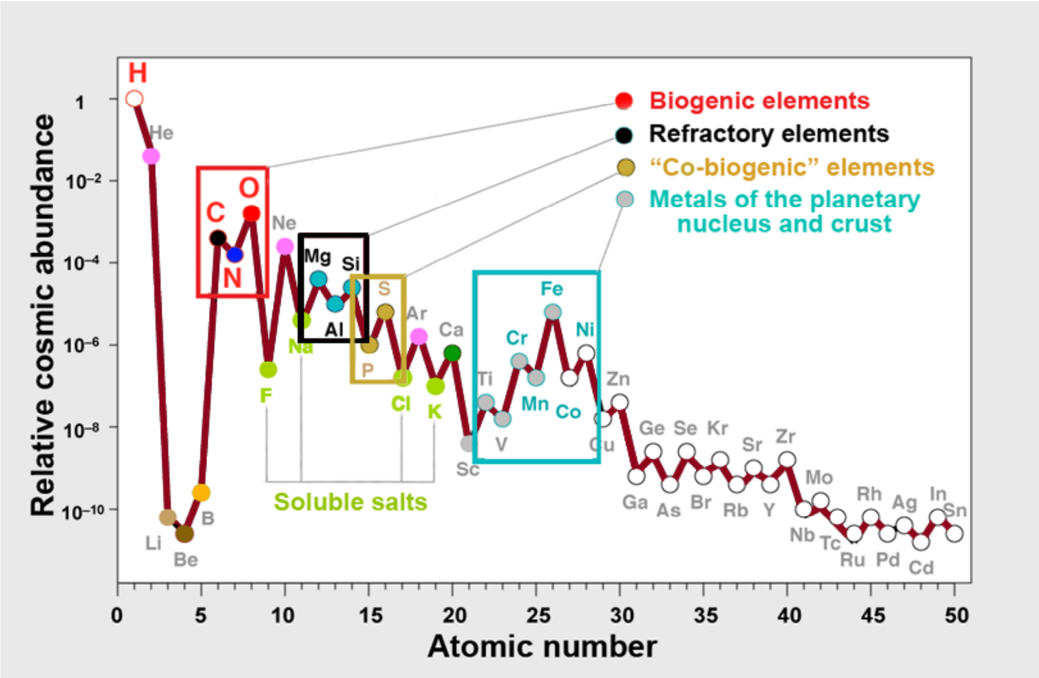

Fig. 67
Cosmic abundance of elements, up to no. 50, with respect to hydrogen.

In the interstellar medium, by its nature extremely rich in hydrogen, it is expected to be with this element that all the other elements primarily bind to produce water, methane and ammonia as the far most abundant compounds in the medium. However, these compounds are not equally stable towards the radiation emitted by stars, so that as the interstellar medium ages, ammonia is the first to disappear by dissociation to produce molecular nitrogen, followed by water to release oxygen, leaving the methane, which is proportionally much more stable. However, being an element much lighter than the others, the hydrogen released in these dissociations will be depleted and scattered in the medium, while the compounds formed are concentrated under the mutual gravitational attraction to form a dense cloud of gas and dust. The molecular nitrogen is almost chemically inert, so inert that we breathe this gas without it interfering with any of our metabolic processes; thus, it remains in this state until it is subjected to sufficiently energetic electric discharges (lightning and auroral displays) to break the bonds in its molecule. In contrast, oxygen, even molecular oxygen, is very reactive, especially under the action of light, and easily reacts with other elements, particularly the refractory elements to form the mineral and the rock materials of dust grains associated with dark molecular clouds, and comets and meteorites. In the vicinity of old stars, where most of the hydro-

gen has been consumed in the formation of heavy nuclides, carbon predominates and then, instead of methane or other light hydrocarbons, PAHs are formed, rich in carbon and poor in hydrogen. We have mentioned that through the action of light PAHs produce important chemical compounds, for example, when they react with oxygen to produce aldehydes and ketones (quinones).

Under the action of energy (light, electric discharges, shock waves) in an interstellar medium with water, methane and ammonia, unsaturated organic compounds are quickly generated, especially formaldehyde and hydrogen cyanide; since they are very reactive, unsaturated compounds are commonly referred to as compounds of high energy, giving spontaneous and, one would say, inevitably more complex materials, as is the case of the ubiquitous amino acids. Up to this point we are in a deterministic Universe in which the destinies of matter are prescribed. However, as chemical systems become more intricate, not only in complexity but also in the variety of new molecules formed, the outcome of chemical reactions will depend increasingly on the physical conditions of the environment (temperature, pressure, distance, radiant energy) and on their natural fluctuations. And so we step from a deterministic Universe to a random, chaotic Universe, in which contingency takes care of the destinies, making outcomes more and more unpredictable. In Greek mythology, chaos was considered the non-organized state, or nothingness, where all things arose. According to Hesiod's Theogony (c. 740–670 BC), Chaos preceded the origin, not only of the world but also of gods. According to the Orphic cosmogony, with roots in the seventh century BC, *Chronus*, the personification of time, gave rise to Ether, the embodiment of energy, and to Chaos, the embodiment of emptiness, from which all things were generated: Heaven, Earth and Eros.

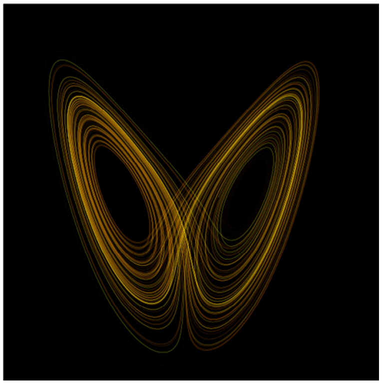

Fig. 68

Lorenz Attractor, generated by equations $dx/dt = -10x + 10y$, $dy/dt = 28x - y - xz$, $dz/dt = -(8/3)z + xy$, in a system of axes x,z. Small differences in a variable produce large differences in the outcome.

URL: ://en.wikipedia.org/wiki/File:Lorenz_attractor_yb.svg

During the first half of last century some physicists and mathematicians have developed an area of mathematics to study nonlinear systems, which by definition are concerned with problems whose variables cannot be described as a linear sum of independent components. In 1961, the American mathematician Edward Lorenz (1917–) found an erratic result when he was making a climate prediction by computer; when investigating this issue he found that there are systems in which small changes in the initial conditions produce large variations in the final outcome of any operation to which they may be submitted (Figs. 68 and 69). This property he called the "butterfly effect" to mean that the beating of wings of a butterfly could, in principle, cause a tornado thousands of miles away. These systems, known as nonlinear dynamical systems are non-deterministic and typical of natural phenomena such as climate and the movement of populations. In 1975, another American mathematician James Yorke (1941–) used for the first time the term chaos in connection with the mathematics of nonlinear systems. The work carried out at that time led to the understanding that, although complex and erratic, these phenomena could be defined by simple mathematical equations. Similarly, systems that were apparently simple and described by deterministic models could lead to very complicated outcomes. However, in exploring the chaotic behavior, it is often possible to understand how the system behaves over time as a whole. Other researchers in this field included the Belgian chemist of Russian origin Ilya Prigogine, (1917–2003), Nobel Prize in Chemistry in 1977, who dedicated himself to the study of self-organizing systems arising out of chaos. Indeed, the development of Chaos Theory has shown that a system passes easily from one state of order to a chaotic state, but that within the chaos order can sometimes arise spontaneously.

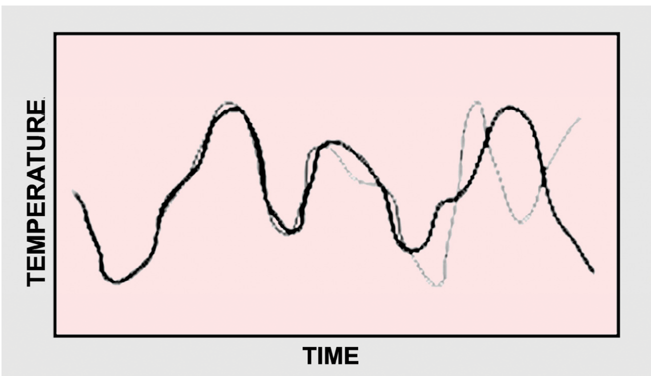

Fig. 69
Curve in black represents the evolution of a chaotic system over time. A small change in initial conditions generates a new curve (represented in gray), which at first almost coincides with the first. However, after some time the two curves differ so much that they in no way resemble each other.

In short, a chaotic system is managed by a set of very simple laws, but laws where any slight variation in the initial conditions can lead to different, unpredictable and very complex developments. And we come back to the initial question: if Life were to rise again on Earth or in some other place in the Universe, would the resulting living beings be similar to those we know? The most likely reply would be no. In fact, according to Prigogine, when the complexity of any system increases, a critical stage can be reached when it begins to function unpredictably; the system will then lose its original conditions so that it will never return to the initial state. It will not be absurd to say that the evolution of Life on Earth may not be repeated here or anywhere else in the Universe. If Life re-emerged, it would certainly follow a path different from that we know.

As a natural phenomenon, Evolution is also a chaotic process where the smallest variation in gene frequencies can lead to unpredictable "futures". This suggests that identification of the different evolutionary factors could lead to finding a single underlying mechanism that might allow a better understanding of Evolution as a whole. On the basis of Chaos Theory, two aspects of the evolving phenomenon could be considered, the first referring to a gradual process of optimization under certain conditions. The second has an adaptive element, which includes the existence of an 'attractor' that keeps the gene "pool" of the species at equilibrium, until the conditions change and allow the emergence of a neighboring 'attractor' that causes the gene pool or part of it to change. In this way many things would be explained, among them the non-Darwinian changes. The mathematical treatment of these systems leads to the conclusion that processes operating within them may amplify small oscillations from equilibrium, leading to huge and unpredictable consequences. This may explain how a slight excess of the L form of an amino acid arising from the action of circularly polarized light at an early stage of chemical evolution might result in homochirality, i.e. the exclusive prevalence of L-amino acids and, indeed, of D-sugars. An alternative explanation has been given by Ilya Prigogine as to how matter, when placed in a strong flow of energy as occurs in the Universe between the torrid stars and the frozen outer space, this matter undergoes auto-organization, apparently in contradiction with the predictions of Lord Kelvin for isolated systems treated by classical Thermodynamics. According to Prigogine, in open systems remote from equilibrium, entropy exchanged with the surroundings may be sufficiently negative in absolute terms, to exceed the variation in internal entropy of the system, in which circumstance the said system will self-organize while this process lasts. When systems increase their complexity, they reach a point of no return and may organize themselves in unpredictable directions, and this may apply to both chemical and biological systems.

THIRD PART

The search for Life beyond the Earth

Introduction

The Universe is not only stranger than we imagine, it is stranger than we can imagine.[1]

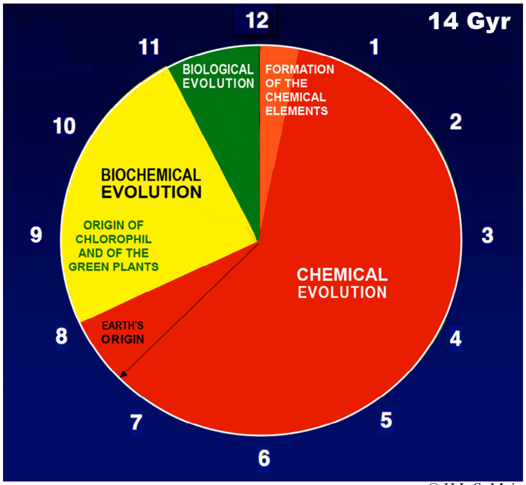

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Fig. 70
"Cosmic clock"
The 12 Gyr in the clock dial does not fit with the most recent data on the age of the Universe, which is believed to be close to 14 Gyr.

WHEN THE UREY-MILLER EXPERIMENT was planned, little was known about the chemical composition of interplanetary space, and almost nothing known about the nature of interstellar space, the only species previously identified being the methylidene radical, CH, and the methylidene ion,CH^+, both found in 1937, and the cyanogen radical, CN, in 1939. The Second World War and the reconstruction effort that followed caused a considerable gap in the development of many sciences, including Astrochemistry. It was only in 1968, fifteen years after the above experiment, that two compounds, ammonia and water, were found in interstellar space. The following year confirmed the presence of formaldehyde (H_2CO), and in 1970 carbon monoxide (CO), hydrogen cyanide (HCN) and others were discovered. By the end of 1971, twenty-one compounds were known to exist in interstellar space. Currently, over 140 different neutral molecules and ions are known, and, in many cases, the reaction pathways to their formation are known with confidence. It is also known that the meteorites from comets and, sometimes from other neighbouring planets can act as messengers carrying relatively developed material, such as amino acids, simple sugars, nucleic acid bases and amphiphilic compounds, produced beyond

1 John B.S. Haldane, in "Possible Worlds and Other Papers", p. 286 (1927).

the Earth. Many years have passed since experiments of prebiotic simulation stopped being focused on our planet by recreating the physical and chemical conditions that were believed to characterize it in its primitive state. In fact, planets and other bodies may exist in our solar system whose physical and chemical conditions may be, even today, similar to those of Earth in its origin.

Fifty years ago the Urey-Miller results may have led many people to believe that this was the way to understand how Life had originated on Earth; today we need to progress to an understanding as to how Life may have originated outside the Earth. Therefore, astrobiologists have investigated the possibility that comets, meteorites and cosmic dust have carried more elaborate biomolecules or even living cells through space, as was originally proposed by advocates of the panspermia model. It follows that, at present, it is a sound scientific premise that Life may have emerged anywhere in the Solar System and then be transported from planet to planet, including our own. Up to a few years ago, it was thought that any expression of Life would require mild environmental conditions so that its delicate materials and biochemical mechanisms could remain intact and operational. One used to impose enormous restrictions on the viability of Life outside of Earth's protective environment. But as new forms of Life are being discovered in some of Earth's most harsh habitats, in which they have developed great resistance and durability, so the panspermia model has regained consistency and credibility.

If on Earth microorganisms are found living in such extreme conditions, it is quite possible that in places like the ice caps of Mars, the oceans of the icy moons of Jupiter or the methane seas of Titan, once considered absolutely unfit to host Life, habitats of extremophiles, similar or different from any of those already known on Earth, might now be found. If there is a subsurface ocean of water on Jupiter's satellite, Europa, for which there is now real evidence, then the existence of Life may be possible, including extremophile organisms associated with hydrothermal vents at the bottom of its ocean. Astrobiology remains alert to exploring all places of extreme life on Earth that may resemble the physicochemical environments being discovered beyond our planet. Thus, the Earth may serve as a laboratory to testing the possibility of survival in our neighbour planets and other planetary bodies. However, while these bodies are gradually revealing their geography, geology and climate through increasingly advanced space missions, we will gain knowledge about the chemistry that first blossomed in this part of the Universe and maybe in the entire cosmos. Below we will describe the results of the principal space missions that have taken place in the search of suitable conditions to sustain Life in other parts of our Solar System.

Chapter 10

The Moon

I think a future flight should include a poet, a priest and a philosopher… we might get a much better idea of what we saw.[1]

Fig. 71
The phases of the Moon, *in* Galileo Galilei (1564–1642), *Siderius Nuncius*, 1616.
URL: http://en.wikipedia.org/wiki/Portal:History_of_science/Previous_pictures#June_30

THE MOON, EARTH'S SINGLE NATURAL satellite, is also the object closest to us, the object that so much influences our lives. It was called *Luna* by the Romans, Selene and Artemis by the Greeks, and by many other names in various mythologies. Recognized since prehistoric times, the Moon has always attracted the attention of man, feeding the

1 Michael Collins (1930–), American astronaut who flew over the Moon.

imagination of Plutarch (Greece, 46–127 AD) in "*De Facie in Orbe Lunae*" (70 AD) and Lucian of Samosata (Syria-Greece, 125–191 BC) in "*Vera Historia*" (180 AD). During the Renaissance this natural curiosity evoked scientific thinking; in the mid-seventeenth century Galileo chose the Moon for his first recorded astronomical observations by telescope. Another astronomer who devoted much time to writing about Life on the Moon was Johannes Kepler (Germany, 1571–1630) in "*Somnium sive opus postumum Astronomy Lunar*" (1634). Probably as a result of Galileo's observations, the seventeenth century became rich in stories about the inhabitants of, or travellers to, the Moon, as, for example, those of Francis Godwin (England, 1562–1633) in "The Man in the Moone" (1638), John Wilkins (England, 1614–1672) in "The Discovery of the World in the Moone", and "A Discourse Tending to Prove That 'Tis Probable There May Be Another Habitable World in That Planet" (1638), Cyrano de Bergerac (France, 1619–1665) in "Histoire Comique des Etats et Empires de la Lune" (1657) and Bernard le Bovier de Fontenelle (France, 1657–1757) in "Entretiens sur la pluralité des mondes" (1686). More recently, interest in our companion satellite seems to have waned, but was revived around the end of the nineteenth century, with Jules Verne (France, 1828–1905) in "De la Terre à la Lune" (1865) and "Autour de la Lune" (1870), Georges Méliès (France, 1861–1938) in "Journey to the Moon" (1902, film) and Herbert George Wells (England, 1866–1946) in "The First Men in the Moon" (1901).

10.1 Visible and invisible aspects of the Moon

Since the Moon has virtually no atmosphere to obscure observation of its surface through a small telescope or even binoculars, we can obtain a clear and informative view of the various lunar features; just by observing it with the naked eye, it is possible to discern two main types of terrain: relatively bright areas and dark plains. But fascination with the unknown and a taste for exploring new worlds have inspired man to imagine the most diverse and daring adventures; its short distance to Earth makes it the most "attractive" extraterrestrial object to explore.

Among its features visible from Earth are craters, dark areas called *maria* (singular *mare*) and light mountainous areas called *terrae*, the Latin term for continent. These terms date from the seventeenth century, when the observers using rudimentary telescopes thought that these dark areas were large surfaces of water. They gave them fanciful and romantic names as *Tranquillitatis Mare* (Sea of Tranquility), *Nubium Mare* (Sea of Clouds), *Nectaris Mare* (Sea of Nectar), *Mare Serenitatis* (Sea of Serenity) and *Mare Inbrium* (Sea of Bath). The *maria* comprise a shape that resembles a human face, sometimes called "Man on the Moon". This name was coined by Francis Godwin in his book of 1638. This 'face' is always looking at us, since the rotation of our satellite has the same period as its translation around the Earth. The side of the Moon that is never visible is often called the "dark side" or "far side" (Fig. 72).

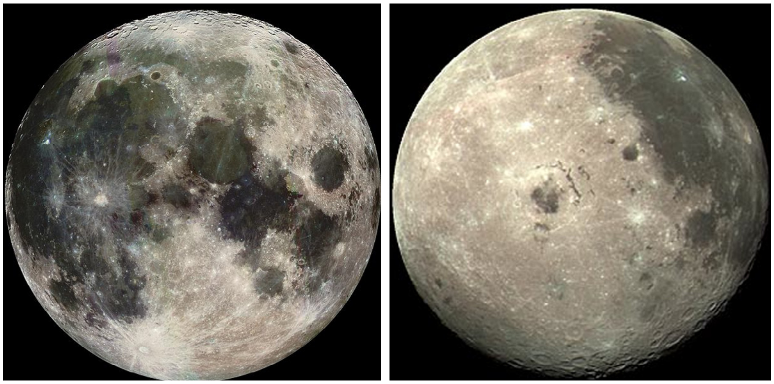

Fig. 72
Left: The visible side of the Moon.
Right: Photograph of part of the backside of the Moon, showing the center of the crater *Mare Orientale*.
Credit: NASA / JPL.
URL, respectively: http://commons.wikimedia.org/wiki/File:Full_moon.jpeg and
http://www.dlr.de/en/DesktopDefault.aspx/tabid-5170/8702_read-16073/8702_page-2/gallery-1/gallery_read-Image.1.8219/

The *maria* have far fewer craters than the surrounding areas, which suggests that they have not been exposed to the bombardment of meteorites for as long as the continents and, therefore, should be relatively young. On the other hand, they have a circular shape suggesting that, like the craters, these depressions were caused by impacts. Names of famous figures in the history of science were assigned to most of the craters, such as Tycho, Copernicus and Ptolemy. In contrast, geographical features on the dark side have modern references such as Apollo, Gagarin and Korolev. In addition to the familiar features in the visible side, the Moon also has large craters at its south pole — Aitken, at the dark side, is 2250 km in diameter and 12 km deep, which makes it the largest impact basin in the Solar System, and *Mare Orientale*, in the west limb is a splendid example of a crater with multiple rings. The *mare* that is facing the Earth is 2 to 5 km below the average lunar *terrae*, while the *terrae* extend several kilometers above the average level. These are often referred to as the highlands and occupy about 84% of the surface, the remaining 16% being occupied by the *maria*.

10.2 Main features of the Moon

THE IMPACTS OF MICROMETEORITES pulverized the rock surfaces, producing fine-grained debris called regolith, which is responsible for the low albedo[2] of the Moon,

2 Albedo is a measure of reflectivity of a body or a surface and measures the ratio between the amount of reflected light and that of incident light.

because they absorb most of the sunlight that reaches them. The regolith, or lunar soil, is composed of unconsolidated mineral grains, rock fragments, and these become welded in the form of glasses as a result of impacts. They can be seen across the whole surface of the planet, with the exception of the steep crater walls and valleys. They have a thickness of 2 to 8 meters in the *maria* and may exceed 15 meters in the *terrae*, depending on how long the bedrock underneath has been exposed to meteors. Under the "Apollo" and "Luna" space programs, 382 kg of lunar rocks and soil were brought to Earth, both from the surface and from below the surface; three main materials of the surface were studied: the regolith, the *maria* and the *terrae*.

All samples returned by the Apollo program are of igneous rocks. Metamorphic or sedimentary species do not exist, which suggests that in the past most of the lunar surface was molten. The lunar rocks are mainly composed of the same materials as found in terrestrial volcanic specimens. The *maria* are covered with basaltic rocks similar to those dark colored rocks formed from volcanic lavas in Hawaii. The continents are made of light rocks called anorthosites. On Earth, anorthositic rock is found only in very ancient mountain ranges. It should be noted that most of the species that were collected were not pure anorthosites, but "impact breccias",[3] formed by different types of rocks that were broken, mixed and melted due to multiple meteorite impacts. It is these materials that provide most of our knowledge of the Moon today; more than 30 years after their collection these precious samples continue to be studied, particularly their dating. Most of the Moon rocks seem to have ages between 4.6 and 3 Gyr. These ages correlate with terrestrial rocks, which are a little over 3 Gyr old.

The Moon has a weak global magnetic field; some of its rocks exhibit remnant magnetism, which indicates it may have had acquired this field early in its history. With no atmosphere, the planet's surface is directly exposed to the solar wind,[4] so that, over time, many protons may be embedded in the Moon's surface. So, samples of rocks brought by the space missions have proved to be a major contribution to the study of the solar wind. Data collected by the "Clementine" probe suggest that ice could exist in some deep craters near the south pole of our satellite, which are always in the shade. This suggestion was confirmed by the "Lunar Prospector" mission. Apparently there is also ice in the north polar region. The average thickness of the Moon's crust is about 68 km and varies essentially from 0 km beneath the Sea of Crises, up to 107 km north of Korolev crater situated on the rear side of the planet. Below the crust there is a mantle and probably a small nucleus with a radius of about 340 km and 2% of the mass of the planet. The Moon's interior is no longer active, and interestingly, its mass center is about 2 km farther from its geometrical center in the direction of Earth. The crust is also thinner on the near side of our planet. Without plate tectonics or erosion caused by an atmosphere or ocean, the only changes that occur on the surface of the moon are due to the fall of meteorites.

3 "Breccias" are rocks formed of angular fragments of minerals cemented in a matrix due to natural causes.
4 The solar wind is a continuous emission of elementary particles of matter (electrons, protons and neutrons) from the surface of the Sun.

10.3 The conquest of the Moon

HISTORICALLY, SPACE EXPLORATION BEGAN with the launch of the artificial satellite, Sputnik, by the U.S.S.R. on the 4th of October of 1957, at the Baikonur Cosmodrome (Tyuratam, Kazakhstan), the Russian rocket launching base. It was this event that triggered a race between the U.S.S.R. and the U.S. for the conquest of space, which culminated with the arrival of Man on the Moon. But in reality, the Moon missions began in 1959 with the Soviet Union sending three spacecraft, "Luna 1", "Luna 2" and "Luna 3", which were the first to pass by, to reach and to collide with the dark side of our satellite, respectively. American attempts to reach the Moon began in early 1960s with project "Ranger" with a spacecraft equipped with television cameras that transmitted close-up images of the lunar surface.

Moon's features [1]

Orbital features		Methane	Traces
Average radius	384 399 km	Ammonia	Traces
Eccentricity	0.0549	Carbon dioxide	Traces
Period of rotation	27 d 7 h 43.7 m	**Crust composition**	
Tilt	5.1454°	Oxygen	43%
It is a satellite of	Earth	Silicon	21%
Physical features		Aluminum	10%
Equatorial diameter	3474.2 km	Calcium	9%
Surface area	3.793×10^7 km^2	Iron	9%
Mass	7.3477×10^{22} kg	Magnesium	5%
Average specific weight	3.3464 g cm^{-3}	Titanium	—
Gravity on the surface	1.622 m s^{-2} (0,1654 G)	Nickel	0.6%
Rotation period	27 d 7 h 43.1 m	Sodium	0.3%
Axial tilt	1.5424°	Cromium	0.2%
Albedo	0.12	Potassium	0.1%
Average surface temper.	–53 °C	Manganese	0.1%
Atmospheric features		Sulfur	0.1%
Atmospheric pressure	3×10^{-15} atmospheres	Phosphorus	500 ppm
Helium	25%	Carbon	100 ppm
Neon	25%	Nitrogen	100 ppm
Hydrogen	23%	Hydrogen	50 ppm
Argon	20%	Helium	20 ppm

[1] URL: http://en.wikipedia.org/wiki/Moon

The first successful landing was achieved in 1966, by the Soviets, with "Luna 9", four months before the U.S. "Surveyor 1" reached the same goal. The "Surveyor" program, between June 1966 and January 1968, consisted of sending five spacecraft that landed successfully. The object of this mission was to send images taken directly from the soil to determine if the ground would be safe for landing a manned spacecraft; these missions showed that the soil was as solid as that of the Earth. Between August 1966 and August 1967 five spacecraft were also released under the U.S. "Lunar Orbiter", program, its aim being to obtain high-resolution images for mapping the entire lunar surface. However, the first satellite to orbit the moon was "Luna 10", four months before this was achieved by the American "Lunar Orbiter 1". The "Lunar Orbiter" spacecraft sent a total of 1950 high-resolution images covering almost the entire surface of the Moon; the detail of these images proved essential for choosing future landing sites.

Fig. 73
Footprint of the astronaut Edwin Eugene Aldrin (1930–), during the Apollo 11 mission, on the dust of the soil (regolith) of the Moon.
Credit: NASA.
URL: http://en.wikipedia.org/wiki/File:Apollo_11_bootprint.jpg

The race between East and West ended in 1969, when "Apollo 11" became the first manned spacecraft to land, and bring back rock and soil samples (Fig. 73). In the following decade, the unmanned Soviet spacecraft "Luna 17" and "Luna 21" placed vehicles that travelled across the lunar surface, while "Luna 16", "Luna 20" and "Luna 24" brought rock samples back to Earth. The analysis of samples retrieved by "Apollo" indicated the presence of a very small amount of carbon (100 ppm) and traces of simple organic compounds such as methane and hydrogen cyanide, probably resulting from implantation by solar winds. However, amino acids were not detected, despite some controversy with respect to the techniques used for analysis. The ab-

sence, or very low amount, of amino acids on the Moon's surface can be understood in view of the high vacuum condition of the lunar surface, and the effects of radiation and high daytime temperatures. To test these effects, irradiation experiments using a solar wind simulator at different temperatures, were performed on a model of the lunar regolith consisting of a mixture of various amino acids in basaltic sand. The results showed that most of the compounds are rapidly destroyed, even when located at the base of the reactor. Calculations from these data showed that on the surface of the Moon these compounds are destroyed relatively quickly (in only 10,000 years). It is therefore likely that the amino acids found in lunar rocks in one laboratory analysis were generated during the analytical treatment from some of the hydrogen cyanide present in the sample.

In 1994, probe "Clementine" spent more than two months observing the Moon from its orbit. This probe was equipped with a wide range of high-resolution cameras sensitive to UV, IR and visible light. The analysis of images obtained from "Clementine" in different regions of the electromagnetic spectrum revealed the composition of the lunar surface. Images at different wavelengths were then used to create a map representing the iron concentration over the surface of the planet. One of the most important of "Clementine's" discoveries was the possibility of the existence of substantial amounts of ice over the south pole. In 1998 the NASA "Lunar Prospector" reinforced "Clementine's" findings, but in 2003 radar observations made from Earth suggested that, if there is ice at the lunar poles, it will be in layers a few centimeters thick.

The probe SMART-1, launched on 27th of September of 2003, was the first mission of the European Space Agency (ESA) to visit the Moon, where it went into orbit in November 2004. It was a long trip only justified by the fact that it used gravitational impulse technology in addition to ion propulsion, instead of conventional chemical fuels, a new technology planned for use in future interplanetary missions. Several scientific instruments were placed on board, some with the aim of studying the performance of the engine and others dedicated to the acquisition of scientific data concerning the Moon. After the American "Lunar Prospector" and "Clementine" missions found evidence of water, the "SMART-1" was launched to test this hypothesis. The probe was equipped with a high resolution miniaturized camera (AMIE) prepared to study the lunar topography and textures. With about one million pixels and filters that allow discernment of the yellow and the short infrared frequencies, and using different observation angles and lighting conditions, the 5 degree field of vision of this camera enabled it to discover new clues about the evolution of the lunar surface. Another important piece of equipment of this probe was a near infrared spectrometer (SIR) to map the distribution of certain minerals on the lunar surface such as pyroxene, olivine and feldspar. Distinguishing 250 wavelengths between 0.9 and 2.4 micrometers, the increased resolution of this instrument allowed it to observe in much more detail than the U.S. probe "Clementine", which could distinguish only six

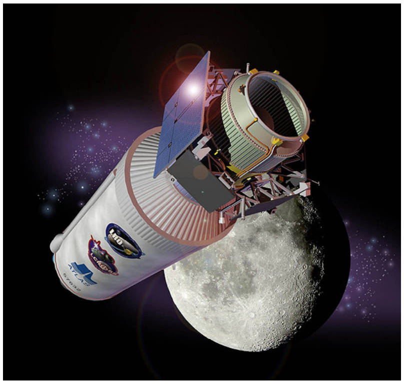

Fig. 74
Lunar spacecraft LCROSS (Lunar Crater Observation and Sensing Satellite) with Centaur Stage, which in November 2009 confirmed that much water exists near the Moon's south pole.
Credit: NASA.
URL: http://en.wikipedia.org/wiki/File:LCROSS_Centaur_1.jpg

IR wavelengths. A very compact X-ray spectrometer (D-CIXS) completed the equipment, this probe being chosen to determine the chemical composition of the planet by the X-ray signatures emitted by elements when excited by sunlight. Although the probe "SMART-1" was deliberately destroyed by impact with the surface of the Moon on the 27th December of 2007, the vast amount of information collected from this mission is still being analyzed and interpreted.

One of the questions that has always disturbed man relates to the origin of the Moon. The current most widely accepted theory refers to a giant impact between Earth and an object the size of Mars in the early formation of the Solar System 4.5 Gyr ago. If this theory is correct, the ratio between the content of iron and that of lighter elements, such as magnesium and aluminum, should be smaller in the Moon than that observed in our planet. The measurement of the relative amounts of these elements, by the X-ray spectrometer D-CIXS, should provide significant clarification of this issue.

The possible existence of water on the Moon has caused a lot of expectation, curiosity and interest within the scientific community. This is a crucial point, since one of the key factors for the existence of Life as we know it, is the existence of this solvent. Finding water on the Moon would also be a key step towards the creation of future lunar bases. However, to have "survived" to the present time this water would have to be in the form of ice in places permanently hidden from the Sun. These locations are at the bottom of craters in the polar regions. Certainly one of the most challenging tasks in the study and decoding of data from "SMART-1" is the search for the signature of water in the spectra obtained by spectrometer SIR and camera AMIE.

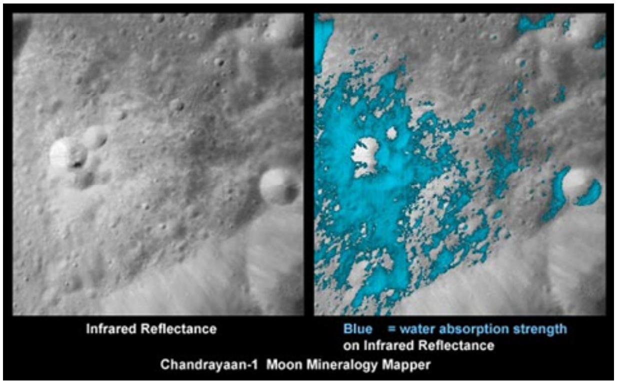

Fig. 75
Views of the Moon's surface by the Moon Mineralogy Mapper on the Indian Space Research Organization's Chandrayaan-1.
Credit: ISRO / NASA / JPL-Caltech / USGS / Brown University.
URL: http://www.nasa.gov/topics/moonmars/features/clark3.html

On 24th of October of 2007 the Chinese space probe "Chang 1" was launched, designed to achieve something similar to the surveys conducted by "SMART-1". More recently, in September 2009 NASA's Chandrayaan-1 mission using the Moon Mineralogy Mapper and, in November 2009 NASA's LCROSS (Lunar Crater Observation and Sensing Satellite) (Fig. 74) have confirmed that much water exists near the southern pole (Fig. 75). This conclusion was made from the detection of IR signals around 2.8 micrometers characteristic of absorption of water molecules and hydroxyl radicals.[5]

5 Not all planned or initiated space missions have been successful; so there is no reason for mentioning them here; apart from justifiable exceptions, this applies to the next chapters.

Chapter 11

Mars

The world is my home, science is my religion.[1]

Fig. 76
Drawing of Mars made by Christiaan Huygens in 1659, showing *Syrtis Major* in the center.
URL: http://kuffner-sternwarte.at/2003/Marsjahr_2003/

References to planet Mars are lost in the mists of time when the Egyptians called it the "Horus of the Horizon" or the "Red Horus" and referred to it as the "planet that goes back". From the times of Aristotle (384–322 BC) and Ptolemy (120–180 AD) until now, the wandering red dot in the night sky has captured the imagination and minds of almost all famous names in the history of Astronomy. Before the invention of astronomical instruments, the observation of Mars was made only by the naked eye, so little was known about it. Most ancient peoples knew that Mars appeared in the northern hemisphere night sky, always in early spring, in the month that gave its name. Its characteristic mark was the reddish color that some peoples associated with the warrior gods. In 1576, the Danish astronomer Tycho Brahe (1546–1601) focused on the

1 Christiaan Huygens (1629–1695), Dutch astronomer.

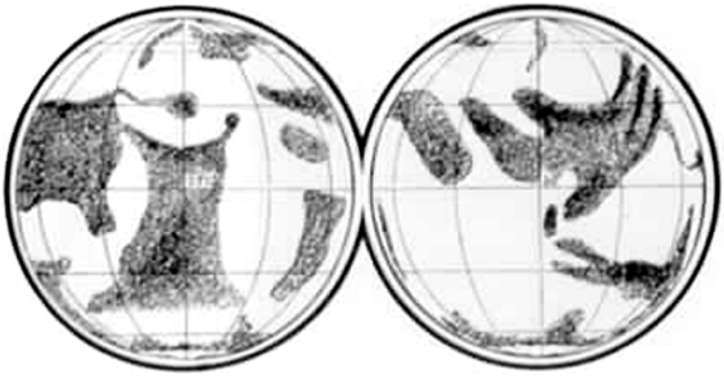

Fig. 77
Map of Mars by Johann Heinrich von Mädler and Wilhelm Wolff Beer, made in 1832–1834.
URL: http://bdaugherty.tripod.com/astronomy/berlin.html

study of this planet's position in the sky. He left his records to his friend Johannes Kepler (1571–1630), to whom they proved essential for developing his laws on planetary motion. Both Brahe and Kepler made naked eye observations, which redoubled the merits of their studies. After the invention of the first astronomical instruments it was possible to obtain more details on Mars. The first telescope was invented by Galileo Galilei (1564–1642) in 1609 and had a magnifying power of 21 times. With it he devoted himself to the observation of the phases of Mars and came to the conclusion that, compared to the Earth, Venus was closer to the Sun, and Mars farther from the Sun. Staying always within the orbit of the Earth, Venus shows us the same phases as the Moon; but Mars, farther from the Sun than Earth, never shows the "new" phases or falcades, i.e. the thin waxing and waning. The person who first made a drawing of Mars was Francesco Fontana (1585 or 1602–1656), a Neapolitan lawyer and astronomer. His drawing of 1636 shows a strange spot in the center of the planet, probably the product of optical defects in the "telescope" that he used.

It is to the Dutch astronomer Christiaan Huygens (1629–1695) that we owe the first descriptions of Mars that have scientific value. In 1655, he concluded that the planet appeared as a disk crossed by a patch of shade. In 1659, he repeated the remark and drew the spots he had traced. He found that the spot in the shape of a V — *Syrtis Major* — was moving slowly and that, later, it was again almost in the same place where he had seen it before (Fig. 76). Huygens eventually deduced that Mars rotates around itself and that, like the Earth, completes one rotation every 24 hours. In fact, the first estimate of its size and the distance from us is also due to him. Later that same year, Giovanni Cassini (1625–1712), an Italian astronomer best known today for the records he made concerning Jupiter and Saturn, reported concealment of a star before it was reached by the disk of Mars, which led him to conclude that the planet has a very dense atmosphere. However, in 1783 William Herschel (1738–1822) showed that this observation was due to an optical

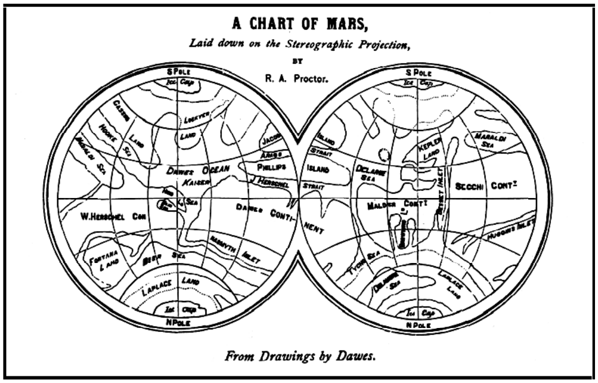

Fig. 78
Map of Mars by William Rutter Dawes, reproduced from the book entitled “Other Worlds Than Ours”, of 1871, written by Richard Anthony Proctor.
URL: http://www.bigear.org/CSMO/HTML/CS05/cs05p02.htm

effect that caused the star to be overshadowed by the scattered brilliance of Mars. With his telescope, Herschel saw that the concealment of stars of small magnitude could occur behind the planetary disc itself, and concluded that Mars has no atmosphere.

11.1 The first maps of Mars

One of the first maps of Mars (Fig. 77) was produced in 1830–1832 by the German banker and astronomer Wilhelm Wolff Beer (1797–1850) in collaboration with Johann Heinrich von Mädler (1794–1874). Another map appeared in 1858, drawn by the Italian priest Angelo Secchi (1818–1878), who gave to *Syrtis Major* the new name “Canale Atlantico” or “Canale Ceruleo”. Less than a decade later, in 1867, the work by the British astronomer Richard Anthony Proctor (1837–1888) became known through the new map of the planet he left us (Fig. 78). After another decade, his compatriot astronomer Nathaniel Green (1823–1899) settled on the island of Madeira in search of better visibility than available in his homeland; with a telescope mounted in Pico do Areeiro, Green in 1877 drew his observations of Mars with great precision (Fig. 79). Comparing these drawings with the assembly of satellite photographs of the end of last century, it is evident that all the major topographical features can be traced; the detail with which he recorded the variations in the extent of the polar cups is remarkable (Fig. 80).

However, it was not Green’s painstaking work that has influenced the mid-century history of Mars observation, but that of his Italian colleague Giovanni Schiaparelli (1835–1910). Schiaparelli’s maps, also dated 1877, were as fine as those of Green, but much more informative. In addition, they were true maps, since all features found were given a name, many of which remain to this day. This astronomer found more or less

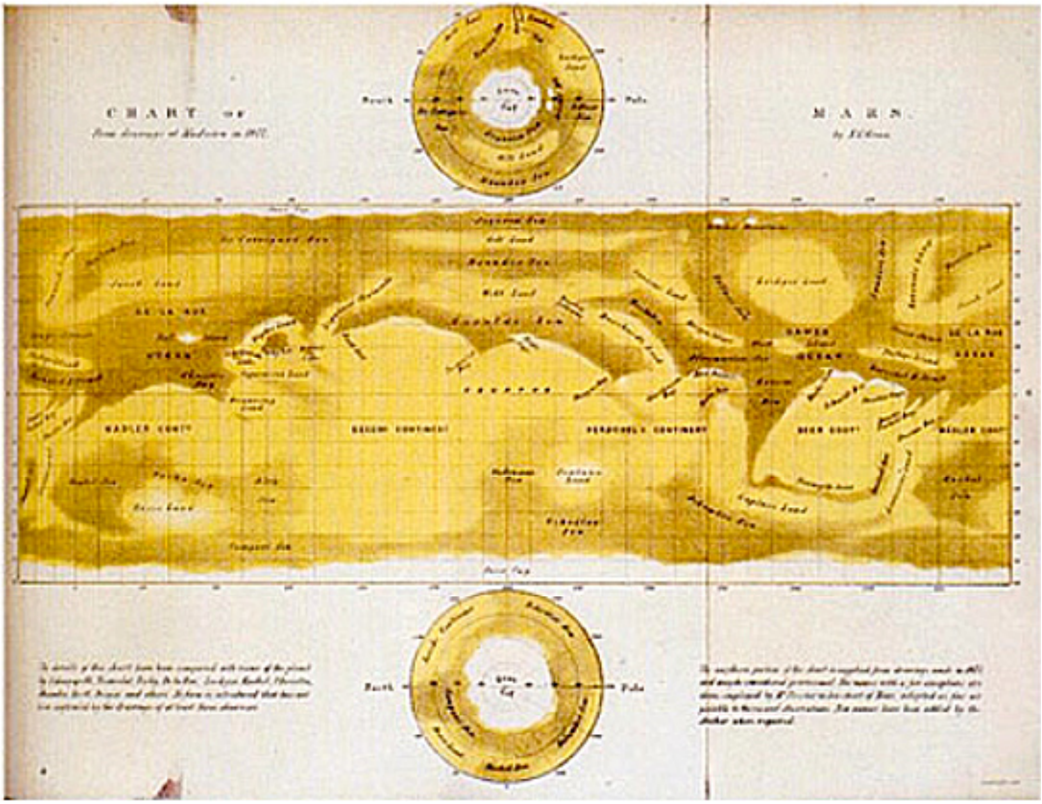

Fig. 79
Map of Mars, drawn in 1877 in Madeira Island by Nathaniel Green.
URL: http://en.wikipedia.org/wiki/index.html?curid=846543

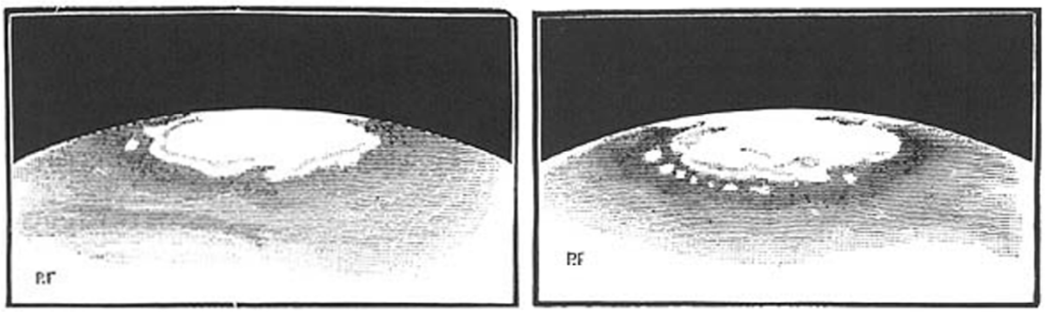

Fig. 80
Evolution of the north polar cap of Mars drawn by Nathaniel Green in 1877.
Credit: Flammarion, “La Planète Mars”.
URL: http://history.nasa.gov/SP-4212/ch1.html

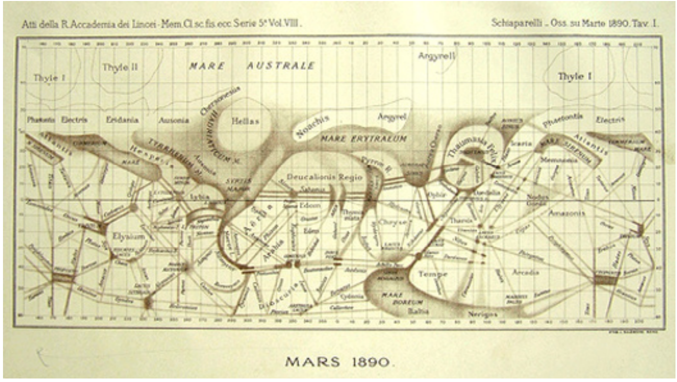

Fig. 81
Map of Mars of 1877, drawn by Giovanni Schiaparelli.
URL: http://bibliodyssey.blogspot.com/2008/04/channelling-martian-maps.html

fine and regular lines on the surface of Mars, along the desert regions of the planet; like Secchi, he called them “canali”, a term that in Italian means any type of watercourse, even natural ones (Fig. 81). Eventually, Schiaparelli’s records became known and “canali” was wrongly translated into English as “canals”, a term that is reserved to describe artificial watercourses. At that time, England was living through the excitement of the important network of channels that British engineers had built skillfully during the previous century. Ultimately this idea that Mars had canals generated fantasies about the possible existence of intelligent life on the red planet and led many to believe that these channels would be engineering works such as those in Britain, but made for the irrigation of the desert regions of the planet.

In the same year (1877), the American astronomer Asaph Hall (1823–1899) observed and identified correctly for the first time, two satellites of Mars. He called them Phobos and Deimos — fear and dread — in honour of Ares, the Greek god of war (Phobos and Deimos were the names of the horses that pulled the war chariot of this god).

The person most influenced by Schiaparelli and who at the same time would influence the following century of observations of Mars was Percival Lowell (1855–1916). A descendent from wealthy American families and intrigued by this planet, he ordered the construction of several astronomical instruments and installed them in a large private observatory, the Lowell Observatory, located in Flagstaff, in the Arizona desert. Lowell devoted himself to studying the surface of Mars and, in particular, its supposed canals, which he drew diligently as recorded in his historical legacy. Obsessed with Schiaparelli’s “canals”, he envisaged in them as the products of an advanced civilization, which sought to prevent depopulation of their planet by constructing canals that led water from the poles to the drier areas at lower latitudes.

This astronomer caught the public imagination with the publication of his books “Mars”, in 1895 (Fig. 82), ‘Mars and its canals’, in 1906, and ‘Mars as the abode of Life’,

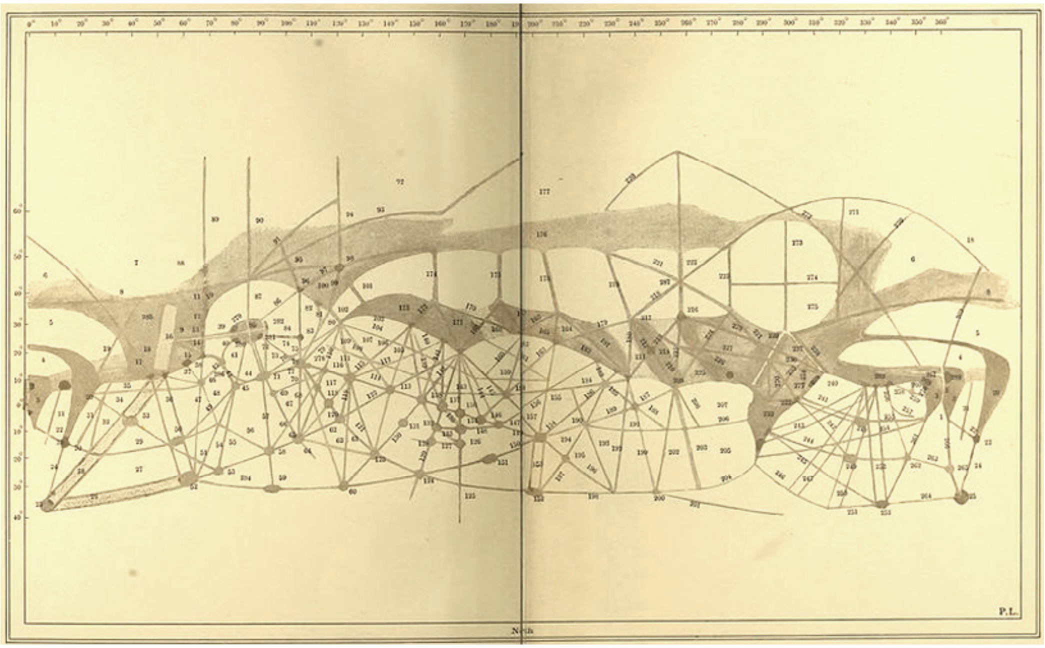

Fig. 82
Map of Mars reproduced from the book “Mars”, of 1895, by Lawrence Percival Lowell.
URL: http://en.wikisource.org/wiki/File:Lowell_-_Mars_%281896%29_-_Plate_24.jpg

in 1908. Adding to the confusion, it had been known for several years that there were some regions in Mars that changed color with the seasons. This was interpreted as the result of foliage fall of vegetation that developed in the warmer months and was in a state of dormancy in the cold months. Despite the impact that these observations had on the public, the community of astronomers never took the details of Lowell’s theory very seriously; eventually it was shown that the supposed canals were no more than shapes produced in the telescope itself by optical effects and also the visual outcome of the movement of dust and clouds. But Schiaparelli firstly, and then Lowell, had prepared the public to be receptive to the works of science fiction writers, who fed the imagination of thousands or millions of readers with their stories and adventures of not only interplanetary Martians and other imaginary people but also terrestrials. These include Camille Flammarion (France, 1842–1925) in “La planète Mars et ses conditions d’habitabilité” (1892), Gustavus William Pope (U.S.A., 1828–1902) in “A Journey to Mars” (1894) and “A Journey to Venus” (1895), H.G. Wells in “The War of the Worlds” (1897), George Chetwynd Griffith-Jones (England, 1857–1906) in “Stories of Other Worlds” (1900) and “A Honeymoon in Space” (1901), and J.H. Rosny (Joseph-Henri Boex) (Belgium, 1856–1940) in “Un Autre Monde” (1910), “La Mort de la Terre” (1910), “Les Navigateurs de l’Infini” (1925) and “Les Astronautes” (1925).

11.2 Main features of Mars

MARS IS THE SEVENTH LARGEST PLANET in the Solar System, the fourth planet counting out from the Sun and the last of the four telluric planets, standing between Earth and the asteroid belt, 1.5 AU[2] from the Sun. Its orbit is significantly elliptical, and between the aphelion and perihelion,[3] this causes the temperature to vary around 30 ºC in the sub-solar region.[4] This has great influence on the climate of Mars — while the average temperature of this planet is about 218 K (–55 ºC), the surface temperatures ranges from 140 K (–133 ºC) at the pole, in winter, to 300 K (27 ºC) during the day in summer. Although Mars is much smaller than Earth, its area is approximately equal to the land of our planet. With the exception of Earth, Mars has the most varied and interesting terrain of the planets of the Solar System, with some spectacular geographical features, among which one may include:

Olympus Mons: the highest mountain in the Solar System, rising 24 km with respect to the surrounding area. Its base is over 500 km in diameter and is surrounded by a cliff 6 km high (Fig. 83).

Tharsis: a large prominence on the Martian surface, 4000 km long and 10 km wide.

Valles Marineris: a system of canyons, 4000 km long and 2 to 7 km deep.

Hellas Planitia: an impact crater in the southern hemisphere over 6 km deep and 2000 km in diameter.

Fig. 83
Olympus Mons, about 600 km in diameter.
Left: View from top. Right: Three dimensional view.
Credit: NASA, JPL-Calltech.
URL, respectively: http://en.wikipedia.org/wiki/File:Olympus_Mons_alt.jpg and http://ciencia.nasa.gov/headlines/y2005/24may_lola.htm

2 AU = Astronomical unit. 1 AU = distance from Earth to the Sun = 149 597 870 km.
3 Aphelion is the point in its orbit where a planet or star is farthest from the orbital center and perihelion is the point in which it is closest.
4 The sub-solar point is the point on the planet that is closest to the Sun ("under" the Sun).

Mars' features [1]

Orbital features		Average specific weight	3.934 g cm^{-3}
Major semi-axis	1.523 662 31 AU	Equatorial gravity	3.69 m s^{-2} (0.376 G)
Perihelion	1.381 333 46 AU	Sidereal day	24 h 37 min 23 s
Aphelion	1.665 991 16 AU	Escape velocity	5.027 km s^{-1}
Orbital circumference	9.553 UA	Albedo	0.15
Eccentricity	0.093 412 33	Temperature range	–87 ºC to –5 ºC average: –46 ºC
Period of rotation	686.960 0 d (1.8808 a)		
Synodical period	779.96 d (2.135 a)	**Atmospheric features**	
Average orbital velocity	24.077 km s^{-1}	Atmospheric pressure	(7–9) × 10^{-3} atm
Tilt	1.850 61°	Carbon dioxide	95.72%
Number of satellites	2	Nitrogen	2.7%
Physical features		Argon	1.6%
Equatorial diameter	6792.4 km	Oxygen	0.2%
Surface area	1.448 984 65 × 10^8 km^2	Carbon monoxide	0.07%
Volume	1.6318 × 10^{11} km^3	Water vapor	0.03%
Mass	6.4185 × 10^{23} kg	Nitric oxide	0.01%

[1] URL: http://en.wikipedia.org/wiki/Mars

A significant part of the Martian surface is old and cratered, but there are younger valleys, mountains and plains. The southern hemisphere of Mars contains predominantly ancient lands generally high with craters similar to those of the Moon. In contrast, most of the northern hemisphere consists of plains much younger and with a much more complex history. The reasons for this global dichotomy are unknown (some experts speculate that it may be due to a large impact shortly after finishing the accretion on Mars).

The interior of the planet is known only by inference from data about the surface and by statistics. The most likely scenario is that it has a dense liquid core about 1700 km in radius, a molten rocky mantle, slightly denser than Earth's, and a thin crust (Fig. 84). Data from the "Mars Global Surveyor" indicate that Mars' crust is about 80 km thick in the southern hemisphere, but only 35 km in the northern hemisphere. The low density of this planet indicates that, in addition to metallic iron and iron sulfide, the core probably contains a relatively large proportion of sulfur.

As with Mercury and the Moon, Mars appears to have no active plate tectonics at present; there is no evidence of recent horizontal movement on its surface, as commonly seen in the folded mountains on Earth. With no horizontal movement of plates, the "hot spots" under the crust stay in a fixed position relatively to the surface. Together with the low gravity on the surface, this may explain the existence of the *Tharsis* prominence and its enormous volcanoes. However, there is no evidence

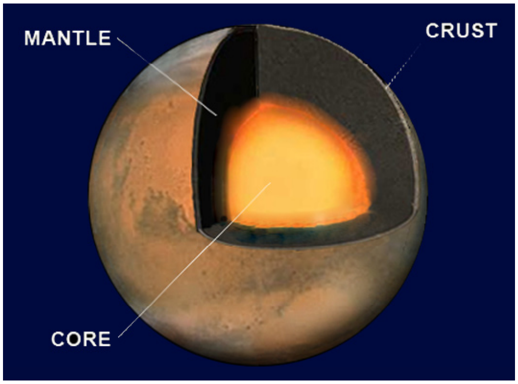

Fig. 84
Structure of Mars.

of present volcanic activity, although data from the probe "Mars Global Surveyor" indicate that Mars may have had tectonic activity in its recent past, which makes comparisons with the Earth more pertinent.

There is clear evidence of erosion in many places on Mars, including large floods and small river systems. In the past there was clearly some kind of fluid on the surface. Liquid water seems to be the obvious choice, but there are other possibilities. There could even be large lakes or oceans; evidence that strengthened this theory was provided by images of layered land, obtained by the "Mars Global Surveyor". But it seems that this occurred for only a short time and long ago; the age of the erosion channels is estimated at about 4 Gyr. It should be noted that *Valles Marineris* was not created by running water, but was formed from strains and fractures of the crust associated with the creation of the prominence of *Tharsis*.

At the beginning of its existence, Mars was much like Earth, and as in our planet, much of the initial carbon dioxide was consumed to form carbonaceous rocks. However, unlike Earth's plate tectonics system, Mars cannot recycle any of the carbon dioxide from its atmosphere. Thus, it does not hold a significant greenhouse effect and, therefore, even if its distance from the Sun were the same as that of the Earth, its surface would be much colder than that of our planet. Mars has a very thin atmosphere, composed mainly of a small amount of remaining carbon dioxide, nitrogen, argon and traces of oxygen and water. The average surface pressure is only 7 millibars[5] (less than 1% of that on Earth), but varies with altitude (from 9 millibars in the deepest basins to about 1 millibar at the top of *Mount Olympus*). However, the atmosphere is thick enough to withstand very high winds and intense dust storms that sometimes "cover up" the entire planet for months.

5 1 Bar = 0.98692 atmospheres.

Mars has permanent ice caps at both poles composed of water ice and solid carbon dioxide (commonly called "dry ice"). These caps exhibit a layer structure in which ice and various concentrations of black powder alternate. When it is summer in the northern hemisphere, the carbon dioxide is completely sublimated, leaving a residual layer of ice. It is likely that a similar layer of ice might exist in the southern hemisphere. The mechanism responsible for the provision of strata is unknown, but may be due to climatic changes related to long-term changes in the tilt of Mars' equator with respect to the plane of its orbit. Ice can also exist hidden beneath the surface at the low latitudes. Seasonal changes in polar ice alter the global atmospheric pressure by about 25% (measured at the landing sites of the "Viking" probes).

The probe "Mars Global Surveyor" has discovered the existence of weak magnetic fields in various regions of Mars, but according to the data collected it woud appear that there was not a global magnetic field. This might have important implications for the inner structure of the planet and for the history of its atmosphere, as well as for the possibility of the existence of Life.

11.3 The beginning of the conquest of Mars

Space exploration of Mars began in 1960 with a first test carried out by the Soviet space agency. Unfortunately, there is very little information concerning the first missions of the U.S.S.R. to Mars, because initially many attempts failed and those responsible had no interest in their disclosure. The information available is fragmentary and contains little reliable data. In 1962, in the Soviet cosmodrome of Baïkonour

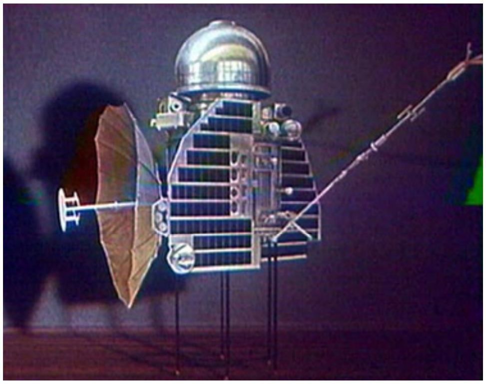

Fig. 85
Spacecraft "Mars 1" of the Soviet space agency, launched to Mars in 1960.
Courtesy of Videocosmos, Moscow, Russia.
URL: http://www.videocosmos.com/images/mars-69/mars-1.jpg

the probe "Sputnik 23" or "Mars 1" (Fig. 85) was launched with the aim of sending to Earth images from Mars. It was the first spacecraft to leave Earth and approach the red planet, passing at about 190,000 km of the planned target. Its success was limited because the mission ended prematurely due to a problem with the guidance system, which led to loss of contact with the base. Nevertheless, 61 radio contacts were established, enabling a large amount of scientific data to be collected, especially information about the solar wind, magnetic fields, cosmic rays and meteor showers.

In 1964, with the start of the "Mariner" programme, it was the Americans' turn to take their first steps towards exploration of this planet. As with the Soviets, some of the probes sent under this program failed. "Mariner 4" (Fig. 86), launched in late 1964, had as its chief aim to make a large number of photographic observations. It therefore contained a television camera mounted on a mobile platform for the study of the planet. However, the probe was due to carry out experiments in Astrophysics (measurement of magnetic fields and particles in interplanetary space and in the neighborhood of the planet); so, most of the other scientific instruments were intended for these purposes. After seven months of travel, the spacecraft reached the orbit of Mars, passing by the planet at an approximate distance of about 9900 km, far closer than the 190,000 km flyby distance of the "Mars 1" spacecraft. During this passage a set of images was obtained covering 1% of the planet, which allowed examination for the first time of its surface details. Nearly three hundred craters, especially in the southern hemisphere, were surveyed having diameters ranging between 5 and 120 km. By observing the images taken by "Mariner 4" the surface of Mars appeared very similar to that of the Moon; this finding destroyed the nineteenth century myth that the red planet was inhabited by an advanced civilization. The existence of a tenuous atmosphere composed of carbon dioxide was also confirmed.

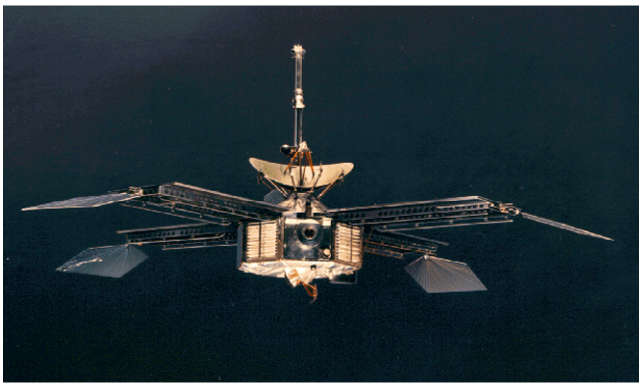

Fig. 86
NASA's spacecraft "Mariner 4", launched in 1964.
Credit: NASA.
URL: http://www.nasm.si.edu/ceps/etp/mars/explore.html

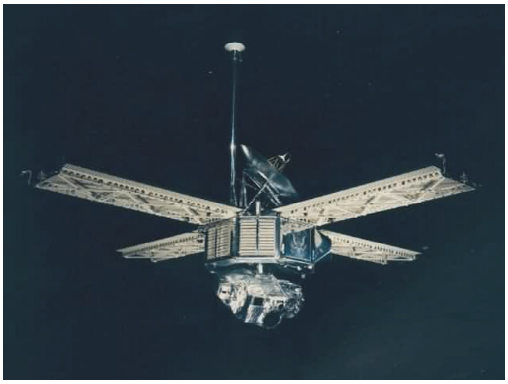

Fig. 87
Spacecrafts “Mariner 6” and “Mariner 7”, launched in 1969, were identical to each other.
Credit: NASA.
URL: http://nssdc.gsfc.nasa.gov/planetary/mars/mariner.html

In 1969, the twin spacecrafts Mariner 6 and Mariner 7 (Fig. 87) departed successfully in the direction of Mars, with the main purpose to study the Martian surface and atmosphere in anticipation of future investigations (in particular the possibility of

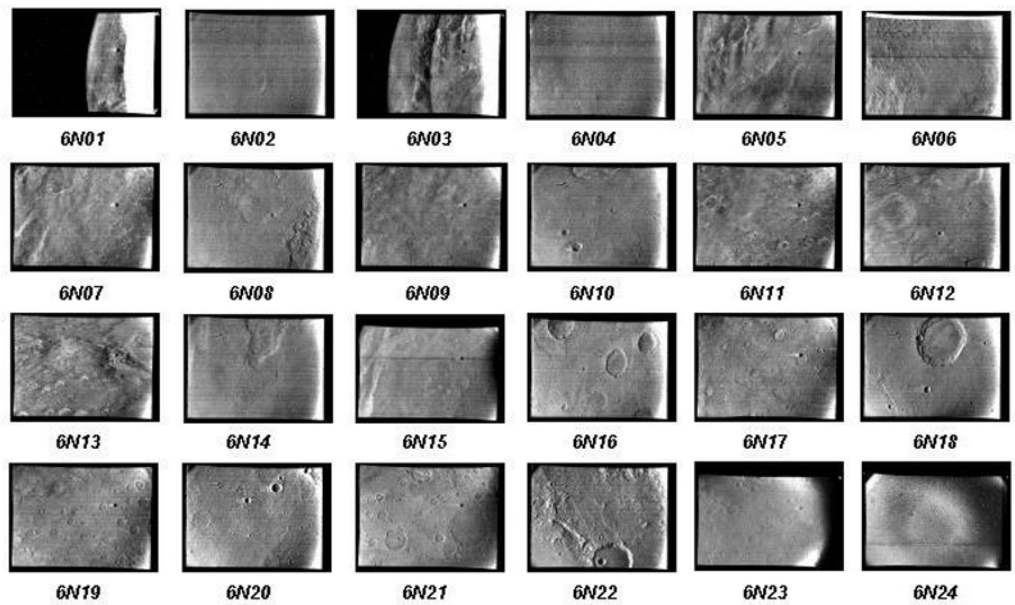

Fig. 88
Photos received from Mars spacecraft “Mariner 6”.
Credit: NASA.
URL: http://planetmars.sites.uol.com.br/explor/sondas/sondas.htm

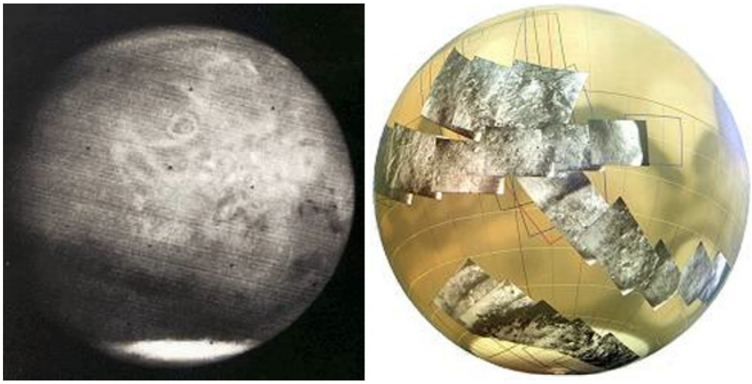

Fig. 89
Left: Photo of Mars taken by spacecraft “Mariner 7”.
Right: Assembly of photographs taken by spacecrafts “Mariner 6” and “Mariner 7”.
Credit: NASA/JPL.
URL: http://www.nirgal.net/explora_1969.html

the existence of Life) and also that of validating techniques that would be necessary to deepen subsequent missions. Five months after its launch, “Mariner 6” arrived at Mars, having achieved a nearest approach of about 3300 km. ‘This enhanced the great American achievement of being the first Men on the Moon, since just ten days before, Neil Armstrong (1930–) and Buzz Aldrin (1930–) had been the first to step onto the soil of our satellite. “Mariner 6” sent a total of 75 photographs, 49 of which related to the Martian globe, and 26 relating to details of its surface (Fig. 88). Amongst these photographs were some relating to one of Mars’ moons — Phobos. This probe provided an improved study of the mass, radius and shape of the planet and its density. By analyzing its atmosphere and surface, it was discovered that the ice cap to the south pole is composed of carbon dioxide.

“Mariner 7” was launched about a month after the “Mariner 6” and reached its destination six days after the arrival of the latter. Its observations were similar and complementary to those carried out by its twin, including 126 photographs, 33 of which concerned the detail of the surface and 93 of the Martian globe (Fig. 89). Observation of the south polar cap showed that its temperature, around –118 ± 10 °C, is almost the freezing temperature of carbon dioxide, which is –125 °C at the atmospheric pressure of Mars. It was thus confirmed, once again, that this cap was not formed by water ice, but by solid carbon dioxide. This gas, the major component of the Mars atmosphere, can therefore condense on the poles when the temperature allows it and volatilize during warmer periods. It became clear that the carbon dioxide cycle is an essential element in the Martian meteorology, a point that strongly differentiates this planet from our own, which is, of course, characterized by the water cycle.

Fig. 90
Photography of Mars craters obtained by spacecraft "Mariner 6".
Credit: NASA.
URL: http://www2.jpl.nasa.gov/files/images/browse/p11331.gif

Observations made by these two probes covered 10% of the Martian surface and revealed an intense activity, as evident from the different shades of soil found throughout the year and the cycle of appearance/disappearance of the polar caps. After studying the images obtained during this dual role, it was possible to distinguish between three types of surface. The most common is that of the regions covered with craters, the southern hemisphere being more rugged (Fig. 90); the second type is constituted by "deserts" without any noticeable relief; and the third type is the most complex to characterize; it is, so to speak, chaotic, the soil being fractured and present as an alternating series of concave and convex areas of hills and depressions. The latter type of terrain suggests some geological activity.

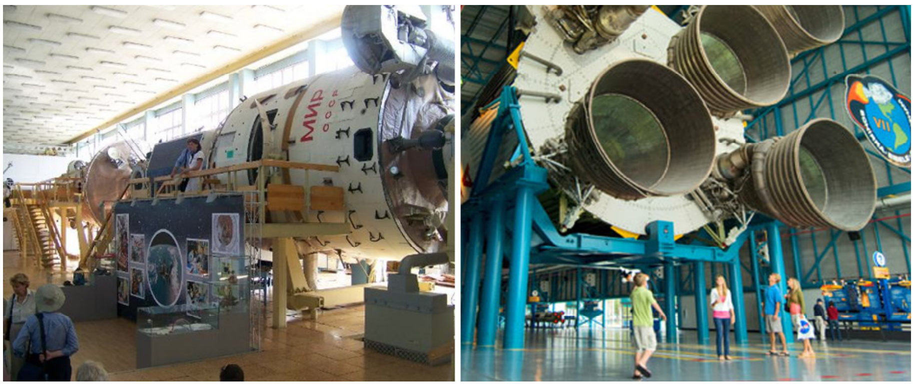

Fig. 91
Guided visits to Gagarin Training Center* (near Moscow) and to Kennedy Space Center† (Florida).
* URL: http://www.waymarking.com/waymarks/WM28AJ_Gagarin_Cosmonaut_Training_Center_Star
† URL: http://www.space-coast.com/KennedySpaceCenterCapeCanaveral/

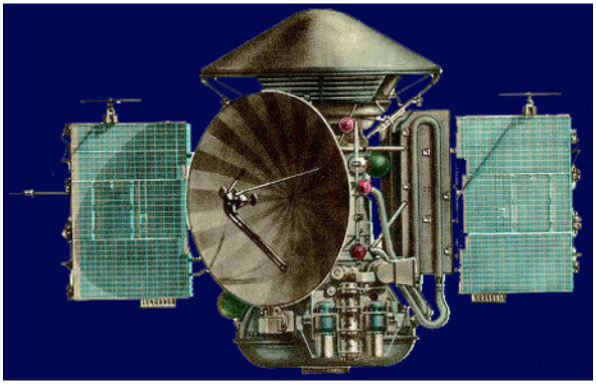

Fig. 92
Twin spacecrafts “Mars 2” and “Mars 3” of the Soviet space agency, launched in 1971.
URL: http://nssdc.gsfc.nasa.gov/nmc/spacecraftOrbit.do?id=1971-045A

11.4 The beginning of the Soviet-American cooperation

THE YEAR 1971 MARKED A MAJOR STEP with regard to the exploration of Mars, a key year in the history of cooperation between the U.S. and the U.S.S.R. Despite the “cold war”, the researchers involved in these missions agreed to exchange results obtained by different probes, for the benefit of both parties. To achieve this objective a telephone line was been installed between the NASA Jet Propulsion Laboratory and the Soviet Institute of Space Research.

Two of the Soviet missions programmed for that year were based on a new strategy. Thus, each spacecraft, the “Mars 1” and “Mars 2” (Fig. 92), involved an orbital module

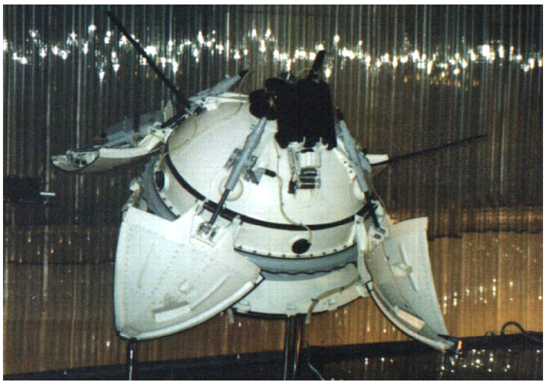

Fig. 93
“Lander” module of the Soviet missions “Mars 2” and “Mars 3”.
URL: http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1971-045D/lec11.html

— "orbiter" — that, as its name implies, was to be put into orbit around Mars, and a surface module — "lander" — destined to land on Martian soil (Fig. 93). The "orbiter" was aimed at investigating the Martian surface from a topographical, chemical and physical point of view, as well as to study the planet's atmosphere and its clouds, the solar wind and magnetic fields. At the same time, it would serve as a relay for communications between Earth and the surface module. When it landed on the planet, it was designed to send pictures of the surface, meteorological measurements (of temperature, pressure, wind velocity and atmospheric composition) and to carry out chemical and mechanical analysis of Martian soil.

The probe "Mars 2" reached Mars in late 1971 and through until 1972 sent data on the atmosphere, surface, gravity, magnetosphere and temperature. Unfortunately the module "lander" reached the end of its life during a sandstorm; it had an inglorious end as it collided heavily with the Martian soil before any further information could be sent.

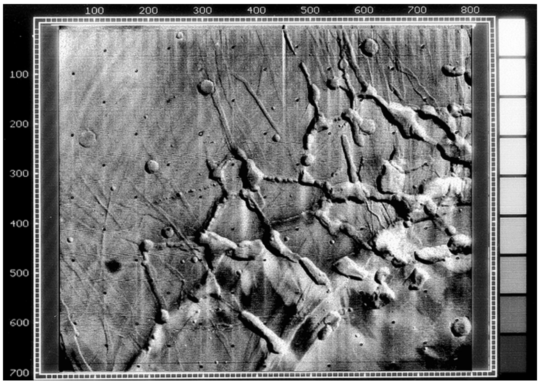

Fig. 94
Mariner 9 view of the "labyrinth" at the western end of Vallis Marineris on Mars.
Credit: NASA, JPL.
URL: http://www.exploringmars.com/missions/mariner9/valley.gif

In contrast to the U.S. probes that could be re-scheduled remotely, the Soviet probes were truly blind robots; they relied on a program loaded on board slightly ahead of the launch, and no possible corrections could be made to deal with contingencies arising from environmental conditions. Nevertheless, this module became the first man-made object to touch the surface of Mars. "Mars 3" was released nine days after "Mars 1, but a fuel leak and loss of data (muting) from the module "lander" shortly after the rendezvous caused the mission to be aborted with its achievement of being the first space craft in the history of space exploration to have landed on the surface of another major planet being thwarted.

On the American side, missions "Mariner 8" and "Mariner 9", planned for 1971, had been scheduled to complement each other. The first was aborted at launch, but the second, after being re-programmed to perform the functions assigned to both of them, arrived at its destination, but not before suffering a mishap. When it was close to reaching its programmed orbit, the spacecraft began to spin, perhaps due to the impact of a small meteorite, but the incident turned out to be of no consequence, since the mission has been most successful. With the 7329 high-resolution images obtained by Mariner 9 the first global map of Mars could be produced. When the probe reached the planet a sandstorm was taking place, which was exploited to obtain data on the phenomenon. The probe revealed channels, volcanoes and other structures — the *Valles Marineris*, named in tribute to the "Mariner 9" (Fig. 94). It also obtained very detailed photographs of Phobos and Deimos, plus "amazing" evidence of liquid water having existed in the past on the Martian surface, as inferred from formations that resemble riverbeds and dry lakes. Mariner 9 continued to provide new data until October 1972.

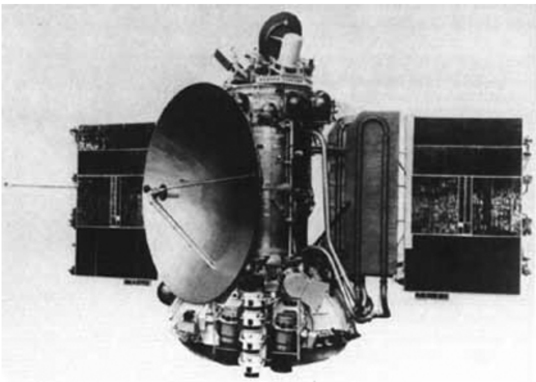

Fig. 95
Soviet space agency spacecraft "Mars 5", launched in 1973.
Credit: NSSDC, GSFC, NASA.
URL: http://nssdc.gsfc.nasa.gov/planetary/image/mars_4.jpg

As the American mission "Viking", scheduled for 1973, was postponed until 1975, the Soviets took advantage of the TIR[6] window of July and August of 1973 to launch four probes to Mars, one after the other, namely two orbital modules with designations "Mars 4" and "Mars 5" (Fig. 95), and two "landers" named "Mars 6" and "Mars 7". The first failed to enter the orbit and disappeared behind the planet, while the latter ceased operating ten days after being placed in orbit. Despite this setback, images were captured that were relevant to the missions that followed. Data were obtained to supple-

6 TIR = Thermal InfraRed. A TIR window is a period of time during which weather conditions are favorable to launch a mission to space.

Fog. 96
Soviet space agency spacecraft “Mars 6”, launched in 1973.
URL: http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1973-052A

ment those that had been obtained by “Mariner 9” on six altimetry profiles, and temperatures of the Martian soil were measured. It was also possible to estimate the size of the smallest constituent particles of eolian deposits as being no more than 0.04 mm across. The land, fractured as a result of tectonic activity, seemed to be formed by granulated material consisting of large grains, crossed with rock layers. The content of potassium, thorium and uranium on the Martian surface, obtained by the gamma-ray spectrometer, was similar to the volcanic ratios rich in iron and magnesium. The photometer, working in the absorption band of water, detected the highest concentration of atmospheric water vapor ever found on Mars towards the south of the Tharsis region. The UV spectrometer dedicated to the measurement of ozone showed that this layer is located at the altitude of 40 km, and that its concentration is 1000 times lower than on Earth. This probe also confirmed that planet Mars has an intrinsic magnetic field, allowing it to be compared with the terrestrial field. Whilst the magnetic north pole on Mars is located in the northern hemisphere, in our planet it is located in the southern hemisphere. With regard to intensity, the magnetic field of Mars is 3000 times weaker than Earth’s, and it tilts by an angle of 15° to 20° with respect to the axis of rotation. The data provided during the radio occultation[7] of the spacecraft “Mars 5”, together with those of probes “Mars 4” and “Mars 6” (Fig. 96) showed that the dark side of Mars actually has an ionosphere, which had not been detected previously. The ionosphere has a peak density of 4600 electrons per cubic centimeter at an altitude of 110 km. The surface pressure reached an average value of $6{,}7 \times 10^{-3}$ atmospheres for the regions surveyed during occultation.

Unlike probes “Mars 2” and “Mars 3”, probes “Mars 6” and “Mars 7” were able to collect data during descent that was immediately relayed to Earth via a carrier platform.

7 “Radio occultation” is the time during which one stops receiving radio signals from the probe, because and while it is orbiting behind the planet.

This was a great advantage, since in case entry into orbit or "rendezvous" with the planet's surface failed, the information about the Martian atmosphere would not be lost. It turned out to be crucial in the particular case of the "Mars 6", as contact with the probe was lost when it was very close to touching Martian soil. After separation from the descent module, the carrier platform flew by Mars at the altitude of 1600 km and for some time relayed the radio emissions of the lander, before leaving in its heliocentric orbit. The data obtained by the probe during descent relating to temperatures and pressures, as well as data from the radar altimeter, the accelerometer and the radio signals concerning Doppler effect[8] measurements, made it possible to reconstruct the vertical structure of the Martian troposphere from the base of the stratosphere at an altitude of 25 km from the surface. They also allowed reconstruction of the variation of density at altitudes between 82 and 12 km. Just before the loss of contact with the probe a pressure of $6{,}1 \times 10^{-3}$ atmospheres was measured, while a thermometer recorded a temperature of –43 °C. An amount of water vapor higher than that generally expected was also found. Although not everything had occurred as predicted, "Mars 6" was the first spacecraft to transmit *in situ* information regarding the Martian atmosphere.

Everything seemed to be indicating that 1973 would become the Soviet's important year with regard to exploration of Mars, but several failures affected the four listed Mars probes and the results were somewhat disappointing. The amount of information collected by these four Soviet probes as a whole was very small as compared with that achieved by the U.S. probe "Mariner 9". This led to "Mars" missions eventually being completely abandoned.

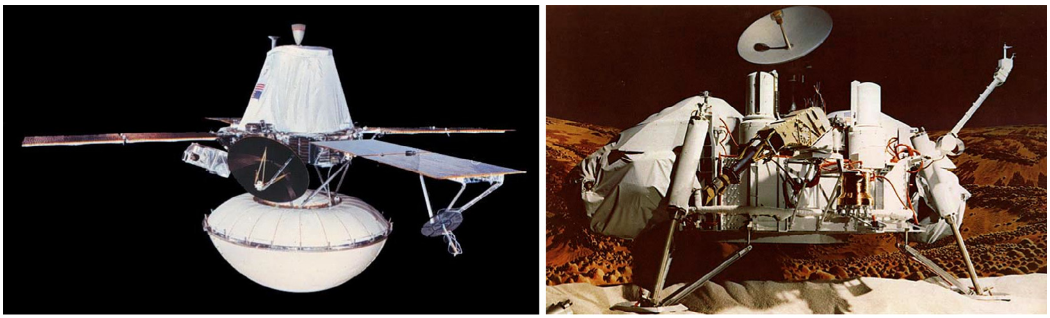

Fig. 97
Missions "Viking 1" and "Viking 2". Left: "orbital" module. Right: "lander" module.
Credit: NASA/GSFC.
URL: http://nssdc.gsfc.nasa.gov/planetary/viking.html

8 When a moving object emits a sound at a given frequency, any stationary recipient receives the same sound at a lower frequency than that emitted if the object moves away and at a higher frequency if it approaches; this effect was characterized by the Austrian physicist and mathematician Johann Christian Andreas Doppler (1803–1853) and became known by his name. The same effect also occurs with the frequency of light and is used in Astronomy and Astronautics to measure the velocity with which celestial bodies move away from us, being more commonly known here by the name "red shift" (or "redshift"), since the frequency of light waves decreases, i.e. wavelength of light waves moves towards the red end of the spectrum.

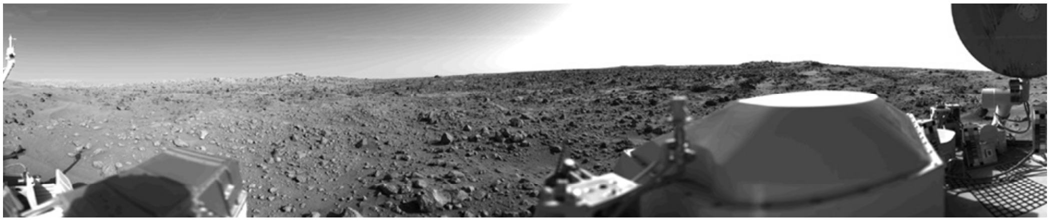

Fig. 98
Panoramic image of *Chryse Planitia* received from mission "Viking 1" on July 20, 1976.
Credit: NASA, GSFC.
URL: http://nssdc.gsfc.nasa.gov/imgcat/hires/vl1_p17045.jpg

The NASA "Viking" mission involved two spacecraft, "Viking 1" and the "Viking 2" (Fig. 97). Each spacecraft consisted of a satellite (orbiter) and a surface module (lander) and these spacecraft were launched separately, twenty days apart. On the 21st of June 1976 the "Viking 1" went into orbit around Mars and began sending photos of possible landing zones for the surface modules. The lander was released and thirty days later it landed west of *Chryse Planitia* (Fig. 98). Twenty-five seconds after landing the first image of the area was transmitted. The main objectives of the mission were to obtain high-resolution images of the Martian surface, to characterize the structure and composition of the atmosphere and of the planet's surface, and to search for evidence of past or present Life. To this end, the satellite and its module were equipped with an IR spectrometer, temperature, wind velocity and wind direction sensors, barometer, and mass and X-ray spectrometers. "Viking 1" made history by being the first mission in which a probe landed safely on another planet. The experimental results were im-

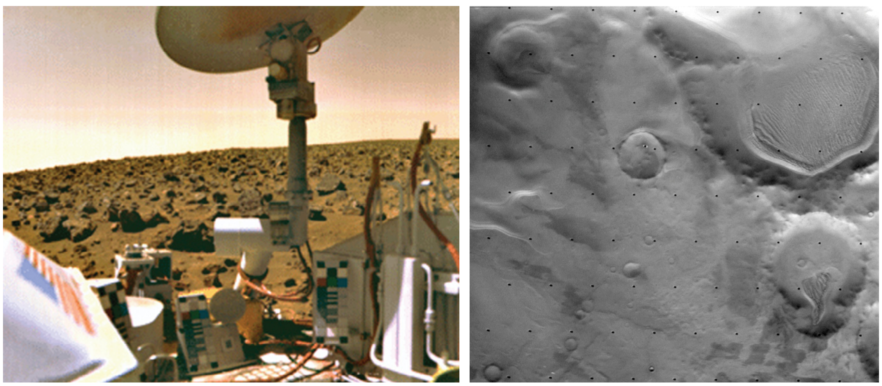

Fig. 99
Images of Mars sent by mission "Viking 2".
Left: *Utopia Planitia*. Right: Area of sand dunes inside an impact crater about 50 km in diameter.
Credit: NSSDC, GSFC, NASA.
URL: http://nssdc.gsfc.nasa.gov/imgcat/hires/vl2_22a166.gif and http://nssdc.gsfc.nasa.gov/imgcat/hires/vo2_479b71.gif

portant because they gave a more complete picture of Mars, with its extinct volcanoes, vast canyons, craters (Fig. 99), formations arising from the wind, seasonal dust storms (Fig. 100), and distinction between the flat and low altitude region in the north, and the southern region of highlands and many craters. The results suggested that there were no microorganisms in the soil — rich in iron — around the surveyed sites. However, more than twenty years later, this conclusion remains controversial, with the suggestion that the mission may have been ill-prepared.

11.5 A concerted program for the exploration of Mars

After the disappointment of "Viking 1" to those who believed in the existence of some form of Life on Mars, the mission that followed was launched only ten years later, in late 1996. It was the "Mars Global Surveyor" (Fig. 101), which was part of a new program to carry out a systematic, consistent and progressive exploration. The trip took almost a year, but it was a year and a half after its arrival that it could begin its scientific mission as it took all that time to change the initial spiral elliptical orbit into a circular orbit around the planet. The objectives of the mission were to obtain high-resolution images of the Martian surface in order to study the topography, climate and gravity, thus characterizing the chemical composition of the surface and atmosphere. It was also intended to carry out a study of the existence and evolution of the planet's magnetic field. Amongst the equipment of "Mars Global Surveyor" was a high resolution camera (MOC), which provided images about the climate of the planet as a whole. A laser altimeter (MOLA) allowed

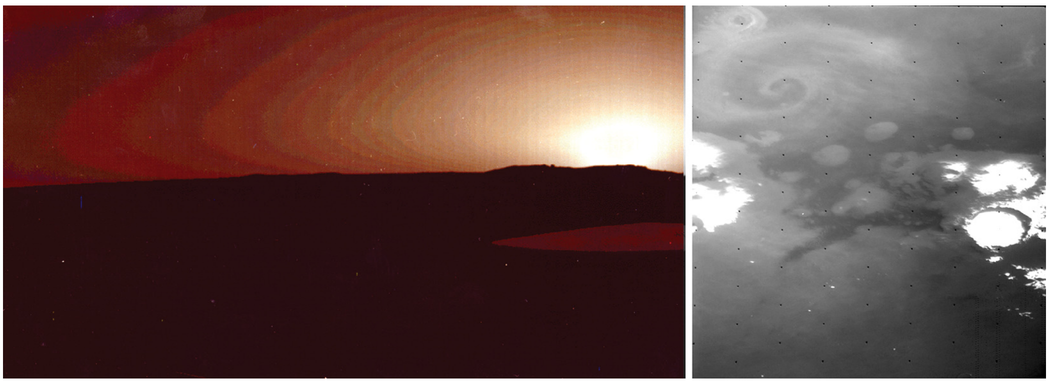

Fig. 100
Images received from Mars mission "Viking 1".
Left: Sunset in *Chryse Planitia*. Right: Cyclonic system near the polar cap.
Credit: NASA, NSSDC.
URL: http://nssdc.gsfc.nasa.gov/imgcat/hires/vl1_12a240.gif and http://nssdc.gsfc.nasa.gov/imgcat/hires/vo1_738a27.gif

Fig. 101
Artist's concept of spacecraft "Mars Global Surveyor".
Credit: NASA, JPL.
URL: http://www.jpl.nasa.gov/history/hires/1996/mars_global_surveyor.jpg

a three-dimensional view of the planet's north pole and the determination of the thickness of the ice layer (between 2 and 2.5 km in the higher latitudes). An electronic reflector magnetometer led to the conclusion that the planet's magnetic field is globally generated in its core, but located in specific areas of the surface (indicating that magma solidified as it came to the surface, having cooled very early during Mars' evolution). Amongst other instruments was a thermal emission spectrometer, which showed a large accumulation of haematite, a mineral that is generated in aqueous media. This mission also obtained information on Phobos, that showed that this planet is covered by a thick layer of powder (about one meter depth), resulting

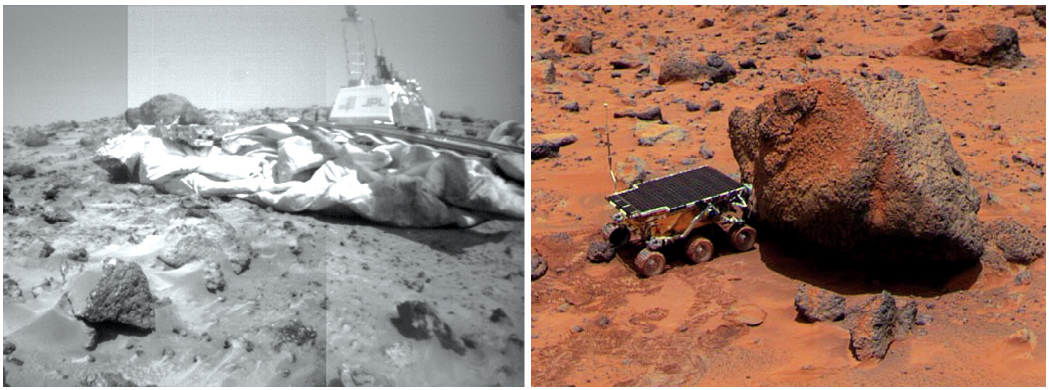

Fig. 102
"Mars Pathfinder" mission. Lander module (left) and the "rover" "Sojourner" (right).
Credit: NASA.
URL: http://nssdc.gsfc.nasa.gov/planetary/marspath_images.html and http://pt.wikipedia.org/wiki/Mars_Pathfinder

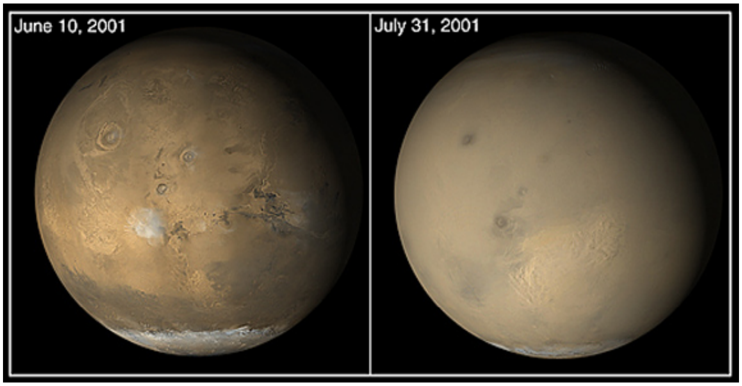

Fig. 103
Mars before (left) and during (right) a sandstorm in 2001, as seen by the Mars Global Surveyor.
Credit: NASA, JPL, Main Space Science Systems.
URL: http://mars.jpl.nasa.gov/mgs/msss/camera/images/E01_E06_sampler2002/dust/index.html

from millions of years of impacts of meteorites and fall of cosmic dust. A variation of about 108 ºC was observed between day and night temperatures; temperatures of –4º C on the sunlit side and –112 ºC of the dark side being recorded. This mission continued sending back millions of images of the planet's surface and many millions of IR spectra until November 2006 when it failed to respond to commands. The mission officially ended in January 2007, but it had been enormously successful, and had additionally located possible landing sites for future missions.

"Mars Pathfinder" (Fig. 102) was the second interplanetary low cost mission launched by NASA, one year after the "Mars Global Surveyor". It consisted of a stationary module and a small "rover" that was given the name "Sojourner". Its aims were to study the atmospheric structure and diurnal and seasonal weather changes in the planet, to describe their rotational and translational movements, and to evaluate the magnetic properties of the soil and its geomorphological and geochemical features. The meteorological sensors detected patterns of diurnal and seasonal temperature and pressure, and indicated that the amount of dust in the air varied very rapidly due to dust storms (Figs. 103 and 104). Important discoveries in the fields of geology, geochemistry and mineralogy were also made, and several small rocks with rounded shape were observed, which led the scientific community to consider that they have suffered erosive action similar to those of terrestrial rocks. This further implies that they may have been transported by rivers, by glaciers or by waves of seas, suggesting an ancient Martian environment rich in water. However, they may also have resulted from fusion of materials during the impact of meteorites, or from pyroclastic explosions[9] in active volcanoes, but records of these events in more recent times of the planet's history have not been found. The mission's X-ray spectrometer gathered data from nine rocks, which enabled

9 Fusion of pre-existing rocks by the action of volcanic or equivalent phenomena.

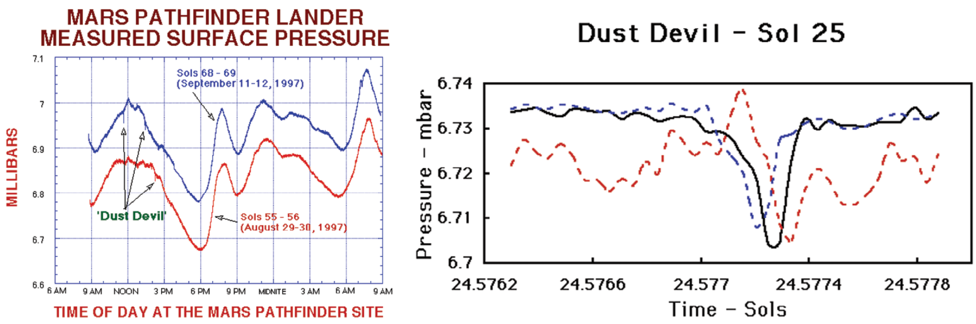

Fig. 104
Data received from "Mars Pathfinder". Left: Difference of pressure between 29-30 August and 11-12 September; the general increase in pressure indicates a decrease in the south polar cap, thereby increasing the amount of carbon dioxide in the atmosphere. Right: Variation of atmospheric pressure during a sandstorm; the dashed lines refer to measurements made by two wind sensors.
Credit: NASA, JPL.
URL: http://marsprogram.jpl.nasa.gov/MPF/science/atmospheric.html

comparison of their composition with that of terrestrial rocks. The conclusion is that the silica content is much higher than that found in the Martian meteorites that fell on Earth; these are the Martian equivalent of terrestrial basalts, while the rocks examined on Mars could be classified as andesites.[10] This was a great surprise and showed that

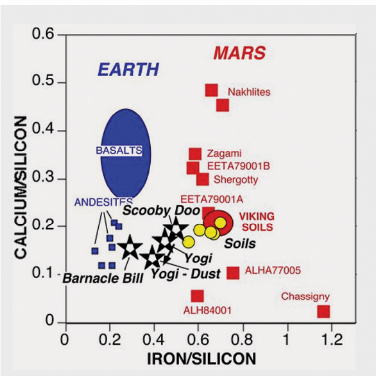

Fig. 105
Composition of Martian soil and rocks obtained by the "Sejourner" as compared with that of terrestrial rocks (white circles and stars, respectively) (basalt and andesite) and also with that obtained from information gathered by the "Viking" mission (larger circle) and also with that of Martian meteorites that fell on Earth (larger squares).
Credit: NASA, JPL.
URL: http://marsprogram.jpl.nasa.gov/MPF/science/mineralogy.html

10 Igneous, volcanic rocks of intermediate composition.

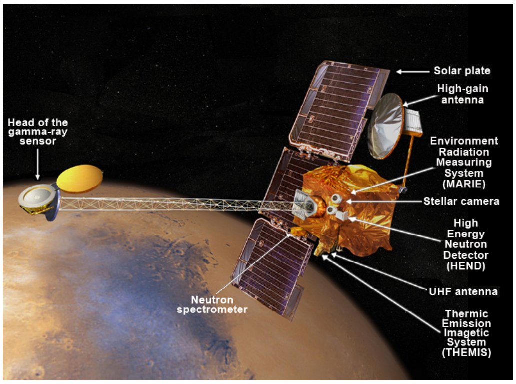

Fig. 106
Artistic image of the spacecraft "2001 Mars Odyssey", where the location of the various instruments that were part of its scientific and operating equipment is indicated.
Credit: NAS/NSSDC. Labeling of the image obtained in
URL: http://nssdc.gsfc.nasa.gov/planetary/image/mars_2001_odyssey.jpg

if the results are representative of the composition of the Martian highlands, then the ancient crust of Mars is similar to the continental crust of Earth, which is quite strange, since the two planets have very different geological histories (Fig. 105).

Mission "2001 Mars Odyssey "(Fig. 106) was launched in April 2001 and reached Mars about half a year later. In January 2002 it had reached a stable orbit and in mid-February was mapping the planet. The mission aimed to gather preliminary data that would help determine whether the Martian environment is favorable or not to the existence of Life, to characterize the geology and climate of this planet and to study the potential dangers from radiation for future manned missions. It was also designed to act as a support to other future exploration missions. Its equipment included a system for measuring the radiation environment of Mars (MARIE) and a system for collecting images of thermal emission (THEMIS), which observes the surface mineralogy of Mars using a visible light and IR camera. With this system, "2001 Mars Odyssey" has taken images that are being used to identify the minerals present in soil and rocks, and the study of small scale geological processes. These images have also allowed selection of the best landing sites for further exploration missions. The equipment also includes a gamma-ray spectrophotometer (GRS) that maps the elemental composition of the surface and determines the abundance of hydrogen in the subsurface, using for such purpose a high energy neutron detector (HEND), a gamma-ray sensor and a neutron spectrometer. The measurement of hydrogen existing just below the soil surface around the globe helped to estimate the extent to which water can exist for future exploration of Mars. This is important, because currently the planet's atmosphere is not dense enough to permit the pres-

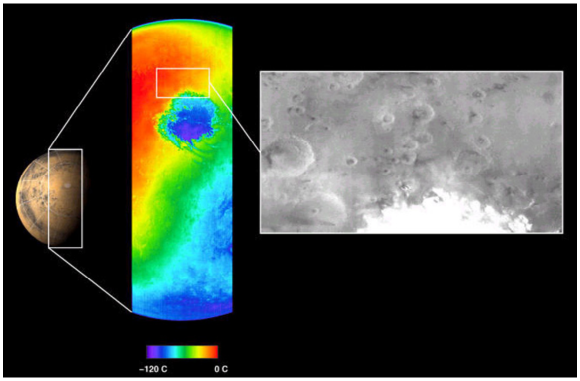

Fig. 107
Thermal emission image of the South Polar cap of Mars (round spot of dark color on the central image, corresponding to a temperature of –120 ºC) obtained on the 2nd November 2001 by mission "2001 Mars Odyssey", and also a visible light partial picture (right).
Credit: NASA/JOL/Arizona State University.
URL: http://www.windows.ucar.edu/tour/link=/mars/images/M2001_big_jpg_image.html

ence of liquid water on the surface. The amount of permanent ice on the planet was also measured (Fig. 107), showing how much it changes with the seasons, having provided conclusive evidence that water exists on the planet. The data supplied clues about the history of the climate and aided understanding of the role of water in its evolution. This was the first spacecraft sent to Mars capable of detecting water deposits near the surface (Figs. 108 and 109). Understanding the nature of

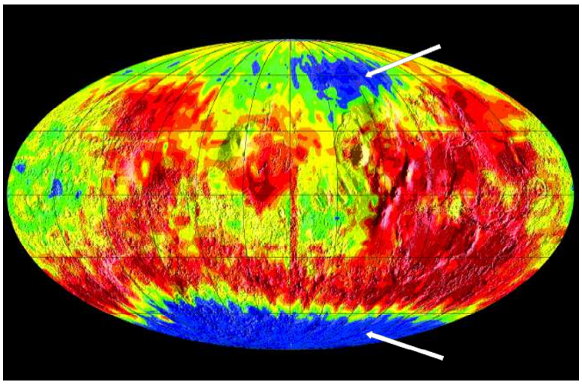

Fig. 108
Image captured by the neutron spectrometer of mission "2001 Mars Odyssey" for detection of hydrogen under the surface of Mars, which should be in the form of water ice. The arrows indicate the two regions in which the concentration of hydrogen is higher.
Credit: NASA. Adapted from
URL http://antwrp.gsfc.nasa.gov/apod/ap020315.html

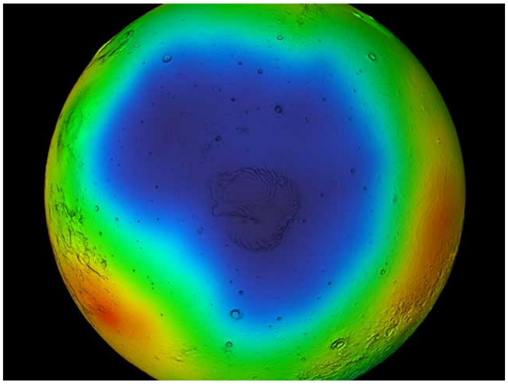

Fig. 109
Image of the North Polar cap of Mars obtained by the neutron spectrometer of mission “2001 Mars Odyssey”. The large blue spot corresponds to hydrogen that is under the surface of Mars, which should be here in the form of water ice.
Credit: NASA, JPL.
URL: http://www.jpl.nasa.gov/images/mars/odyssey-062603-summer-browse.jpg

the chemical elements and minerals that make up the planet has provided valuable information not only about its climatic history, but also about its geological history and potential to harbor Life, now or in the past.

11.6 New Mars missions

THE FIRST ESA MISSION, NAMED “MARS Express”, followed in 2003 and was launched from the Russian base at Baïkonour, in Kazakhstan. “Mars Express” was an orbital module, carrying a robot “lander” that had received the name “Beagle 2” and was intended to travel over the Martian soil. This module was released, but unfortunately it was not possible to establish contact with it, so this part of the mission was reported as lost. Meanwhile, the “Mars Express” has been successful with regard to the orbiter, as contact with the spacecraft has been maintained during the entire voyage, allowing the permanent use of their instruments. In January 2004, the camera HRSC obtained a picture of the Mars “Grand Canyon” (*Valles Marineris*) (Fig. 110). It was the first image of this size where one can see the surface of Mars in high resolution, in color and in three dimensions. The total land area covered was 120,000 km^2. During the mapping of ice in the south pole region with the mineralogical mapping IR spectrometer (OMEGA), water and carbon dioxide in solid form were discovered. This information was confirmed by the Planetary Fourier Spectrometer (PFS), which also showed a different distribution of carbon oxides in the north and south poles. The

Fig. 110
Image of *Valles Marineris*, the Mars "Grand Canyon", as photographed by mission "Mars Express".
Credit: ESA, DLR, Free University of Berlin, (G. Neukum).
URL: http://apod.nasa.gov/apod/ap040124.html

PFS also confirmed the existence of methane in the Martian atmosphere, this being only about ten parts per billion of the total composition of the atmosphere, which shows that its production is very low. However, in some regions of the planet the concentration of methane is 3.5 times higher. Since this gas is relatively unstable and oxidizes in just a few hundred years to give rise to water and carbon dioxide (these exist in the Martian atmosphere with a relative abundance), these differences indicate that nowadays there is production of methane on Mars. It is now important to discover the mechanism by which it is generated; it seems likely to be the same mechanism

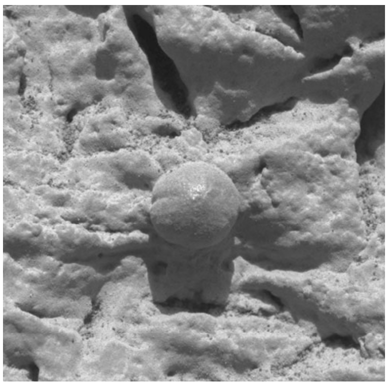

Fig. 111
Image of the rock "El Capitan" (1.7 cm^2) where one can see a mineral little sphere, obtained by mission "Opportunity".
Credit: NASA, JPL.
URL: http://science.nasa.gov/headlines/y2004/images/meridianiwater/bb1_big.jpg

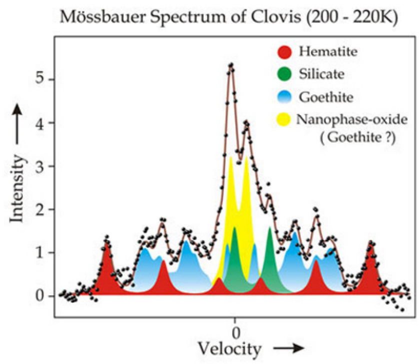

Fig. 112
Mössbauer spectrum of rock "Clovis" of Mars. The presence of goethite in this rock, a mineral that in its composition contains water in the form of hydroxyl radicals, produces strong evidence that in the past there was water on Mars.
Credit: NASA, JPL, Cornell, University of Mainz.
URL: http://athena.cornell.edu/the_mission/ins_moss.html

that generates water, since their atmospheric and subterranean abundances match in terms of spatial location. This mechanism may be volcanic or hydrothermal, as occurs on Earth. However, these hypotheses require confirmation or refutation, and also extensive data collection, analysis and investigation.

The NASA mission that followed was named "Mars Exploration Rover" (MER) and consisted of two twin spacecraft with names "Spirit" and "Opportunity". "Spirit" was released in mid-2003 and "Opportunity" about a month later, reaching their target with 21 days apart, after a six month voyage. The main objectives of this mission were to search and study different types of rocks and soils that could hold clues for the existence of water in the past, to map the rocks and soils around the landing site, to determine the cause of soil erosion, to measure the constitution of the soil in sites that are observed by satellite, and to search for minerals that contained iron and water or that may have formed in water. All this was aimed at providing clues about the environmental characteristics at the time that liquid water existed. "Opportunity" was the first to achieve interesting results, as it landed near some rocks (Fig. 111) that, after being analyzed, provided evidence for the existence of salt water, a favorable and necessary condition for the existence of Life in the past and the possibility of the existence of fossils of living organisms (although "MER" was not equipped for this type of mission). In January 2005, "Opportunity" found a meteorite on the surface of Mars. This is the first meteorite to be identified on another planet; it was the size of a basketball and composed mainly of iron and nickel. It was a very interesting discovery and suggests that some of the rocks previously analyzed could be stony meteorites, since these should be much more abundant than iron meteorites. "Spirit" was dedicated to the study

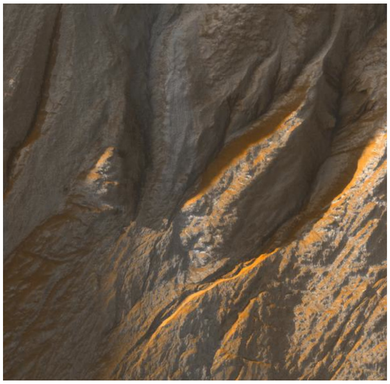

Fig 113
Image of ravines in a crater in *Terra Sirenum* region on Mars, obtained by mission "Mars Reconnaissance Orbiter" on the 3rd October 2006.
Credit: NASA, JPL, Arizona State University.
URL: http://photojournal.jpl.nasa.gov/jpegMod/PIA01923_modest.jpg

of a flat region where there were volcanic rocks and impact craters. It also found evidence for the existence of small amounts of water causing cracks in rocks and minerals such as goethite and jarosite,[11] these being ferrous minerals that on Earth are formed in wetlands (Fig. 112), and hematite. At present, both "Spirit" as "Opportunity" continue to send back pictures of Mars. By January 2009 both rovers had collectively sent back 250,000 images and had travelled over 21 kilometers! However, in April 2009 'Spirit' became embedded in deep Martian sand from which it could not be extracted, and it was decided in January 2010 that it will now be used as a stationary research platform.

In mid-2005 NASA mission "Mars Reconnaissance Orbiter" was launched with very ambitious targets. Amongst these was the search for the existence of Life, or evidence of its existence in the past, and the study of climate and geological history of the planet in order to follow the "water path". During the first week of observations from low orbit, the spacecraft revealed new clues about recent and ancient environments on the red planet (Fig. 113). A year after the launch it had already sent more than 3000 images, including photographs of "Spirit" and of "Viking" (Fig. 114). New images are still being received but during 2009 certain computer software problems arose which temporarily curtailed the collection of new images.

In August 2007, with the collaboration of Germany, Switzerland and Canada, NASA launched a new mission to Mars under the name "Phoenix", which landed safely in May 2008 (Fig. 115). Mission "2001 Mars Odyssey" had shown that large quantities of water ice should exist just below the surface in the planet's northern pole and, therefore, the objective of "Phoenix" is to land in that area and investigate the history of water, the

11 Goethite and jarosite are rocks consisting of hydrated iron and of iron and potassium sulfate, respectively.

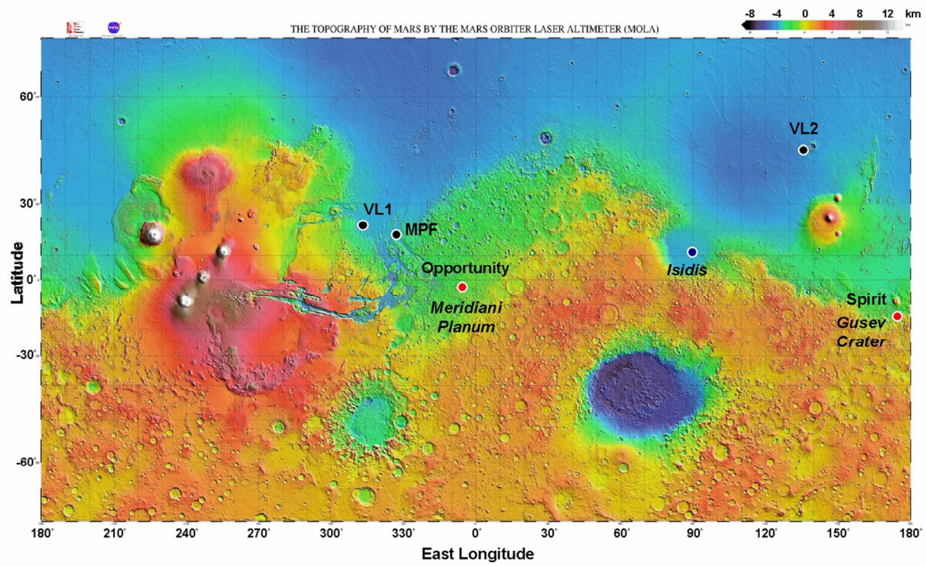

Fig. 114
Planisphere of Mars showing the locations where several spacecrafts landed. "Opportunity", "Spirit", "Viking Lander 1" and "Viking Lander 2" (VL1 and VL2), "2Mars Pathfinder" (MPF) and where module ESA "Beagle 2" would have landed.
Credit NASA, JPL, GSFC.
URL: http://marsrovers.nasa.gov/gallery/landingsites/20051026a.html

way in which polar dynamics have affected the climate and whether the environment below the surface could have been a favorable habitat for microbial life. The "rover" is

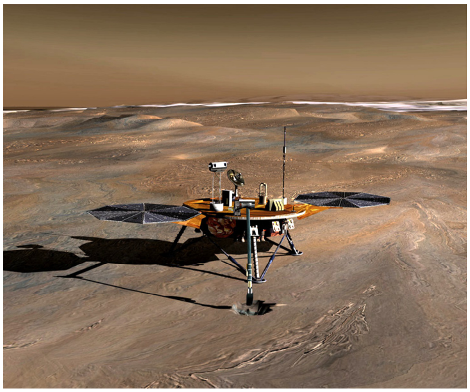

Fig. 115
Artist's image of spacecraft "Phoenix" sent to Mars in August 2007.
Credit: NASA, JPL.
URL: http://mars.jpl.nasa.gov/newsroom/pressreleases/images/phoenixPress_br2.jpg

Fig. 116
Artist's image of "Mars Science Laboratory".
Credit: NASA, JPL.
URL: http://www.jpl.nasa.gov/images/msl/PIA04892-browse.jpg

equipped with a robotic arm for digging the soil around it, in addition to a miniature greenhouse and a mass spectrometer to analyze trace amounts of matter; it also has an integrated chemical laboratory for characterizing the soil and the chemistry associated with ice, and very powerful imaging equipment. To date Phoenix's cameras have returned more than 25,000 pictures from sweeping vistas to near atomic level resolution using the first atomic force microscope ever used outside Earth. The findings advance the goal of studying whether Mars could ever have been favorable to microbial life.

Scheduled for launch in September 2011 with arrival at its destination about a year later, the "Mars Science Laboratory" (Fig. 116) is a mission for exploration of the Martian surface using a "rover" built upon the knowledge gained with the "Mars Exploration Rover". It will have a truly international flavour, with contributions from several countries, including Russia, Spain, Canada and Germany. This will be the first mission to use techniques with precision landing, entering the Martian atmosphere in a controlled manner similar to the entry of the space shuttles in the Earth's atmosphere. It will collect and analyse samples of soil and rocks in the search for organic compounds and environmental conditions that could harbor past and present microbial life forms. Its equipment will detect proteins, amino acids and other acids and bases that may link to carbon chains and be essential for Life. It will also consider other features, such as atmospheric gases that may be associated with biological activity.

Chapter 12

Europa

I should disclose and publish to the world the occasion of discovering and observing four planets, never seen from the beginning of the world up to our times…[1]

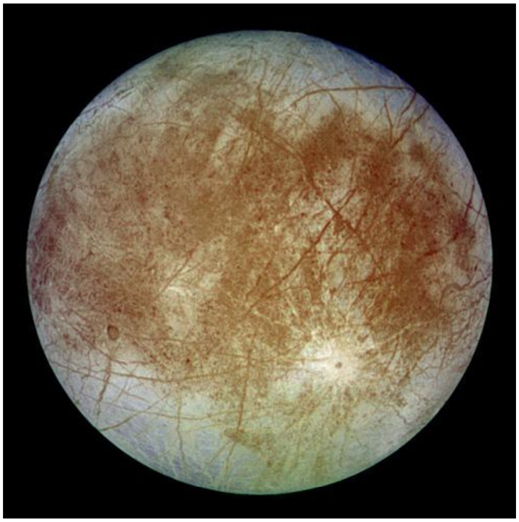

Fig. 117
Planet Europa, a satellite of Jupiter, photographed by mission “Galileo”, in December 1997.
Credit: NASA.
URL: http://en.wikipedia.org/wiki/File:Europa-moon.jpg

TOGETHER WITH IO, GANYMEDE AND Callisto, Europa is one of Jupiter’s moons (the fourth largest) whose discovery was published in 1610 by Galileo Galilei. Although the German astronomer Simon Mayer, or Marius, (1573–1624) had claimed to have discovered these four satellites in November 1609, i.e. two months before Galileo, it was not possible to confirm this because he failed to publish his findings. So, the discovery of these four moons was forever linked to the Florentine astronomer, who named them “Medician Planets” in honour of the powerful Medici family. In 1614, Mayer gave them the names they now have, with the following explanation:

1 Galileo Galilei (1564–1642), *in Sidereus Nuncius*, March 1610.

> "Jupiter is much blamed by the poets on account of his irregular loves. Three maidens are especially mentioned as having been clandestinely courted by Jupiter with success. Io,[2] daughter of the River, Inachus, Callisto[3] of Lycaon, Europa[4] of Agenor. Then there was Ganymede,[5] the handsome son of King Tros, whom Jupiter, having taken on the form of an eagle, transported to heaven on his back, as poets fabulously tell . . . . I think, therefore, that I shall not have done amiss if the First is called by me Io, the Second Europa, the Third, on account of its majesty of light, Ganymede, the Fourth Callisto...
>
> This fancy, and the particular names given, were suggested to me by Kepler, Imperial Astronomer, when we met at Ratisbon fair in October 1613. So if, as a jest, and in memory of our friendship then begun, I hail him as joint father of these four stars, again I shall not be doing wrong".

However, these names were little used until the mid-nineteenth century. By then Europa was mentioned in most of the scientific literature only by its former Roman numerical designation, i.e. Jupiter II, which means "the second satellite of Jupiter.

Europa has unique characteristics, showing a very bright icy surface, intersected by colored stripes. It is believed to be an oceanic world covered by an ice cap. Due to the conditions existing within this oceanic world, some authors think that it might contain Life as exists in the deep seas of Earth. Together with Mars, it seems to be the most likely place to find extraterrestrial life. However, as will be seen below, the information we have on Europa is still very limited.

12.1 First images of Europa

EUROPA AND THE OTHER GALILEAN MOONS are four celestial bodies of considerable size; two of them are larger than Mercury and Pluto, and Io and Europa compete in size with the Earth's moon. These moons can be visible to the naked eye in clear skies and just after sunset. At night the brightness of Jupiter hides them. To see them clearly a good pair of binoculars or a small telescope is required, and even with the best telescopes, very little was known about this planet and its siblings until the mid-twentieth. Only when probes "Pioneer 10" and "Pioneer 11" arrived at Jupiter in 1973 and 1974, respectively, was it possible to determine reasonably accurate masses, and capture the first images of the two major moons of Jupiter. Images of Europa showed little variation in color, revealing a dark area without details, as the probe "Pioneer" was not close enough to provide good surface details. However, as Europa was one of the brightest satellites, it was believed that its crust was mainly composed of water ice.

2 Io was a river nymph, daughter of Inachus, a god of rivers.
3 Callisto was a nymph favorite of Diana, the virgin goddess.
4 Europa was a Phoenician princess, daughter of Agenor and Telefasa.
5 Ganymede was the son of the king of Troy.

Fig. 118
Artist's image of "Galileo" spacecraft.
Credit: NASA, JPL.
URL: http://en.wikipedia.org/wiki/File:P46382.gif

In 1979, the two "Voyager" probes reached Jupiter. In the low-resolution images of "Voyager 1", Europa showed a very large number of lines that intersect. These lines were reminiscent of the channels that some astronomers once claimed they saw on Mars. It was then admitted that they were ground cracks as a result of tectonic processes, but the high-resolution images of Voyager 2" brought surprise to the scientific community, since these lines seemed to be painted on the surface, with no visible topographic relief. The probe "Voyager" mapped in high resolution only a portion of the surface. However, on the 7th December 1995, probe "Galileo" reached Jupiter and was the first probe to orbit this satellite. As will be seen below, most of our present knowledge of Europa was derived from the extensive observations made by this probe (Fig. 118).

12.2 Main features of Europa

EUROPA'S ALBEDO IS THE LARGEST AMONGST Jupiter's four moons, which suggests a young and active surface. Being composed primarily of silicate rocks, this moon looks like the terrestrial planets and is a satellite with dimensions comparable to the Earth's moon. Its density is also similar, slightly lower, which is consistent with the presence of about 5% water at the planet's surface in the form of ice. If this is confirmed, Europa would be the only place (known) in the Solar System, apart from Earth, where liquid water would exist in significant quantities. In 1998, NASA announced that the probe "Voyager" had found strong evidence of a salty ocean beneath the surface of Europa. The maximum temperature at the surface of this planet is –148 ºC, at the equator, and the minimum is –223 ºC, at the poles. Recent data from probe "Galileo" indicate that Europa

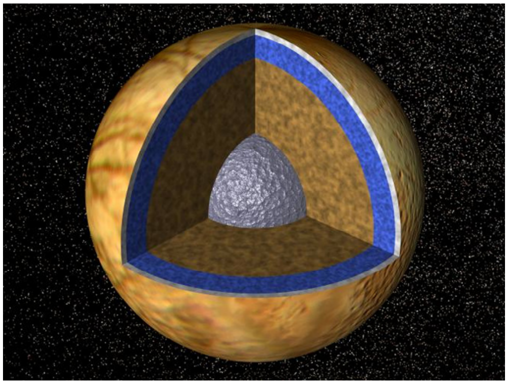

Fig. 119
Predictable structure of Europa, a small metallic core, a rocky mantle, a layer of liquid water and, finally, a crust of solid water.
Credit: NASA, JPL.
URL: http://photojournal.jpl.nasa.gov/jpegMod/PIA01130_modest.jpg

has a layered internal structure, with probably a small metallic core surrounded by a rock layer, and this in turn is surrounded by a global 100 km deep ocean of liquid water, twice the amount of water of all oceans on Earth: a layer of water ice would form the crust of the planet (Fig. 119). According to some specialists, despite the very low surface temperatures, the water will remain liquid in the interior due to the friction caused by very strong tides due to the close proximity of the giant planet Jupiter. Nevertheless, owing to extremely low temperatures at the surface, the ice may be as hard as rock with a thickness of 10 to 30 km. Data obtained by NASA's Voyager show that Europa has a small magnetic

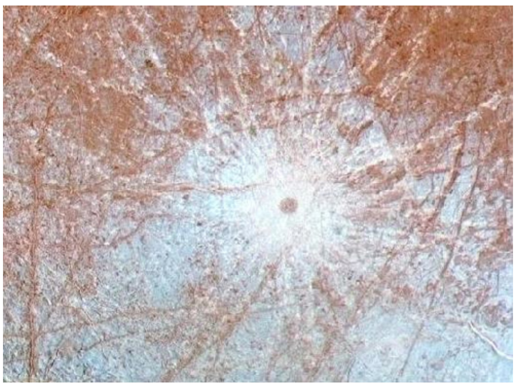

Fig. 120
Crater Pwill in Europa is about 38 km in diameter.
Credit: Galileo Project, JPL, NASA.
URL: http://apod.nasa.gov/apod/ap970417.html

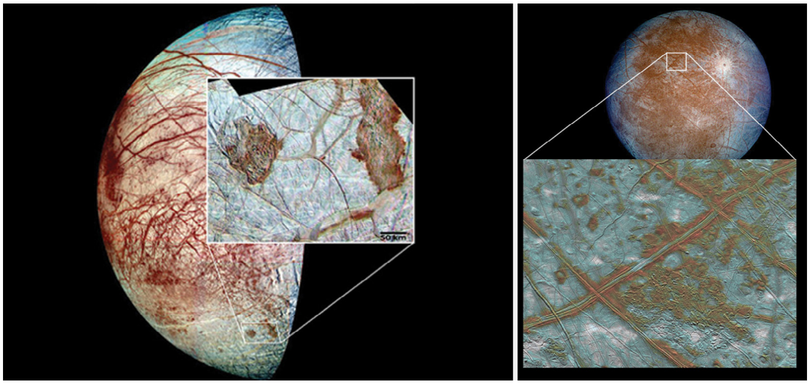

Fig. 121
Details of Europa's surface obtained by NASA's probe "Galileo".
Credit: NASA, JPL, Arizona State University, California Indtitute of Technology.
URL: http://www.ztn.net/mars/solarsystem/europa-galileo.jpg and http://www.lunar.org/docs/nasa/oceans.shtml

field generated by interaction with Jupiter and varying periodically whenever it passes through Jupiter's massive magnetic field. Europa's surface is different from any other object of the inner solar system, being extremely flat, showing few distinct morphological details of small relief. In Europa, craters are rare; the three largest ones, with diameters between 37.4 and 50 km, were given the names Taliesin, Pwyll (Fig. 120) and Midir. The precise age of Europa's surface is still an unanswered question; based on estimates of bombardment by comets, which appear to have been scarce, it probably will be no more than 30 million years old.

What becomes more apparent in Europa are the numerous and intricate line formations across its globe, irregular and random in distribution, some of them reaching 1000 km long. They appeared to form ridges and, in regions where the crust is broken, the two edges of both sides split and diverge from each other, similar to the frozen seas of our planet; this feature clearly supports the presumption of liquid water beneath the surface layer. From spectroscopic data it was ascertained that the dark red colored lines observed on the moon's surface are rich in minerals, magnesium sulfate being among them. Salts would be deposited on the surface by water from the interior and these would change quickly to the vapor state by sublimation. When pure, these materials are colorless or white; so, it is likely that the presence of iron salts is responsible for their red color. It has also been proposed, not without some boldness, that the red color may result from some form of extremophile life of the type found on Earth that exhibits a similar color. The lines may have been produced by geysers or water eruptions occurring after the icy surface has become fractured, with some resemblance to the oceanic rifts of our planet. The differences between the shapes of these lines led scientists to believe that the rotation velocity of the surface of Europa could be a little larger than that of its interior, as if the ocean that seems to exist below the surface acted as a lubricant. A comparison of photo-

Europa's features [1]

Orbital features		Volume	1.593×10^{10} km^3
Perihelion	0.004 44 AU	Mass	4.80×10^{22} kg
Aphelion	0.004 53 AU	Average specific weight	3.014 g cm^{-3}
Orbital circumference	0.028 AU	Equatorial gravity	1.314 m s^{-2} (0.134 G)
Eccentricity	0.009 4	Sidereal day	3 d 13 h 13 m 42 s [3]
Period of rotation	3.551 181 041 d	Escape velocity	2.025 km s^{-1}
Average orbital velocity	13.741 km s^{-1}	Albedo	0.67
Tilt	0.469º [2]	Temperature range	–223 ºC to –148 ºC
Physical features		**Atmospheric features**	
Equatorial diameter	3121.6 km	Atmospheric pressure	10^{-11} atmospheres
Surface area	3.09×10^{7} km^2	Oxygen	100%

[1] URL: http://en.wikipedia.org/wiki/Europa_(moon) [2] In relation to Jupiter's equator. [2] Synchronous rotation.

graphs of probe "Voyager" with probe "Galileo" suggests that it will take 10,000 years for the crust to advance a full lap over the planet's interior. In addition to the lines and few craters, black spots of varying shapes and sizes can also be observed that are referred to as "cryovolcanoes" and may have resulted from phenomena associated with moving water or ice across the surface.

Recently, data from the Hubble Space Telescope on Europa has revealed that this planet has a very thin atmosphere (10^{-11} atmospheres) composed of oxygen, almost certainly of non-biological origin. This gas is probably generated by photodissociation of water due to the solar radiation, with the very light hydrogen that is generated at the same time being lost by depletion. In some areas a type of cloud was observed that may consist of droplets of ammonia. If the existence of an ocean covered with a layer of ice were to be confirmed, and if there is any volcanic activity in the ocean floor as exists on Earth, then one can predict the possibility of underwater life analogous to that associated with the hydrothermal vents in the deep oceans of our planet. The bacterium *Deinococcus radiodurans*, or a close relative, would be a type that might be able to survive in Europa's environment. In order to preserve this planet from possible contamination with terrestrial microorganisms, probe "Galileo" was sent to Jupiter to be destroyed at the end of its mission.

NASA's plans to send a new mission to Europa, "Europa Orbiter", scheduled for launch in 2008, has now been postponed until 2020 as a result of false starts and budget cuts. A mission to the vicinity of Jupiter may require five or more years to reach its destination, so no new interesting results will be available in the immediate future.

Chapter 13

Titan

I had ambition not only to go farther than any man had ever been before, but as far as it was possible for a man to go.[1]

Fig. 122
Planet Titan, a satellite of Saturn.
Credit: NASA, JPL, Caltech.
URL: http://www.tivas.org.uk/solsys/tas_solsys_satsat.html

IN 1655, UNDER THE TITLE "*DE SATURNI LUNA Observatio Nova*", the Dutch astronomer Christiaan Huygens (1629–1695) published his discovery of the second largest moon of Saturn, which he then named "*Luna Saturni*". In 1847, the English astronomer John Herschel (1792–1871), son of the famous English but German-born astronomer William Herschel (1738–1822), proposed that the seven satellites of Saturn be given the names of the Titans of Greek mythology based on the Theogony of Hesiod; they were the brothers and sisters of "*Chronus*" (Saturn in Roman mythology), the youngest son of "*Uranus*" and "Gaia" (Earth). To the moon discovered by Huygens, Herschel proposed the name Titan. In 1907 the Catalan astronomer José Comas y Solá (1868–1937), announced the discovery of a dark limb on the surface of Titan, which led him to suggest the possibility that the planet has an atmosphere. The dark color and rather homogeneous surface that characterized it sup-

1 Captain James R. Cook's Diaries (1728–1779).

ported this idea until 1944, when the American astronomer of Dutch origin Gerard Kuiper (1905–1973) was able to confirm it from spectroscopic data, by obtaining evidence of the presence of methane in this satellite. Its discovery came to the attention of all who were interested in the issue of the origin of Life, since the importance of methane in the early evolution for Life had been admitted for a long time. Having in mind the currently known features of Titan, its present chemistry will greatly resemble that which existed on early Earth and this planet is, therefore, perhaps the most promising candidate of our solar system to supply vital clues as to how and why Life emerged.

13.1 Titan's Place in the Solar System

WHEN, DURING FORMATION OF THE SOLAR System, the Sun was formed, the heat that it irradiated volatilized all materials in its vicinity and the solar wind swept them away from the star; as they became more remote the ambient temperature fell until the materials condensed and eventually solidified. This resulted in a heterogeneous (anisotropic) distribution of the elements and compounds, in such a way that the planets nearest the Sun became essentially rocks (rich in silicon and silicates), while those further away were poor in silicon and rich in elements and other materials that on Earth, for example, would be gaseous or liquid (namely, hydrogen, methane and water). The separation between these "two worlds" is defined by the Asteroid Belt that lies between the orbits of Mars and Jupiter (Fig. 123). All bodies lying closer towards the Sun than this Belt are rocky (terrestrial planets: Mercury, Venus, Earth and Mars, and also the Moon). The remaining bodies are rich in volatiles (Jovian planets: Jupiter, Saturn, Uranus and Neptune, and

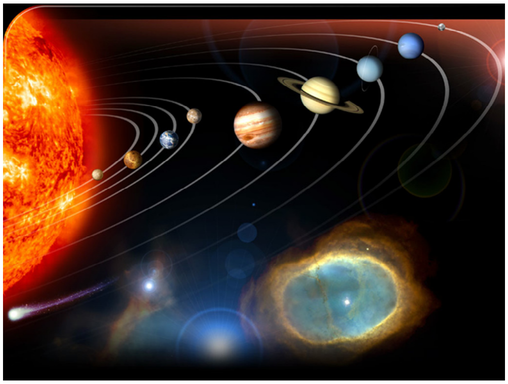

Fig. 123
The Solar System. The diameter of the Sun and of that of each planet shown here as well as the orbits of the latter are roughly proportional to their actual size. However, the diameters of the orbits are represented on a very small scale compared with those of the corresponding planets.
Credit: NASA, JPL.
URL: http://scienceclass.ning.com/

Fig. 124
Comparison of Titan's size with that of the terrestrial planets and the moons of Jupiter and Earth. Titan is only slightly larger than Mercury and Callisto.

also their moons). Beyond the dwarf planet Pluto is the Kuiper Belt with tens of thousands of small frozen bodies, probably all with essentially Jovian features. The above description of the mechanism that led to the uneven distribution of materials in the Solar System (the most dense in the interior and the less dense in the outside) is perhaps an approximation to reality. Indeed, other factors may have acted on this process since the moons of Jupiter and Saturn have compositions that differ from each other and from the planets they are orbiting.

With the exception of Mercury, which is too near the Sun and has a small diameter and a low mass, all the terrestrial planets have an atmosphere. However, almost all the planetary satellites of the Solar System are not large enough to hold gaseous materials. Titan is an exception, because it is neither a large planet (although larger than Mercury) nor a terrestrial planet (Fig. 124), and does have an atmosphere. Titan is therefore one of the most interesting objects in the Solar System, not falling clearly into either of the categories mentioned. For a long time it was wrongly considered the largest moon in the solar system, but only recently, from images taken by Hubble Space Telescope, it was shown that its atmosphere, with a surface pressure one and a half times that of Earth's atmosphere, contributed to this planet appearing to be larger than it actually is. In conclusion, Venus, Earth, Mars and Titan are the only four objects in the Solar System that have dense atmospheres, which makes Titan a very special case. Whilst the relative density of Earth and of the other terrestrial planets is about 5 (relative to water = 1), that of Titan and the other moons of Saturn is about 1.8. This low density indicates that these planets should not have a metallic core and would be relatively poor in silicates. They should instead consist of a rocky core of silicate, surrounded by several thick layers of ices, which contribute to a major proportion of its mass and leading to them being known as icy planets. The interior of Titan may contain ammonia and also methane, both in the liquid state because of the effect of compression from the weight of the upper layers of the satellite. However, Titan is relatively unlikely to contain liquid water, even in its interior, which may cause a fundamental difference in its chemistry from that associated with the earlier stages of hotter planets such as Earth and Mars.

13.2 What one might predict about Titan

Since Kuiper identified methane in Titan's atmosphere from spectroscopic data, numerous questions have arisen about the phenomena and processes that would occur as a result of the presence of this hydrocarbon. The interest in using this satellite of Saturn to help unravel some secrets about the origin of Life increased significantly once it became known that this moon had an atmosphere. The first interplanetary mission sent to explore Saturn was the probe "Pioneer 11", which reached the planet in 1979 and confirmed the existence of a dense atmosphere on Titan. Spacecraft "Voyager 1" (Fig. 125) followed it in 1980, and "Voyager 2" in the following year. The former passed at a distance of 4400 km from Titan's surface and the second was headed in a different direction. The data sent by "Voyager 1" answered some questions but raised others. The intensity of light reflected by the atmosphere of Titan that telescopes are able to capture is low. Adding to this difficulty is the fact that its atmosphere is not only opaque to visible light but also to UV light, because methane absorbs within almost the entire extent of this spectral region. Thus, most of the observations of Titan were made in the IR band, but there is only a narrow window of wavelengths here in which light reflected by the surface can pass through the atmosphere. In its path, "Voyager 1" is now behind Titan, a stage designated in Astronautics by occultation, which led, as always, to the loss of the radio signal emitted by the main antenna. However, before disappearing completely, there was a brief period in which there was a gradual attenuation caused by the atmosphere. The analysis of the signal emitted during this period allowed an estimate of the average molecular mass of the atmosphere of 27 Da.[2] From the gases that are abundant in the Solar System and that plausibly could prevail in this atmosphere there are two whose molecular mass is 28 Da; they are carbon monoxide and nitrogen. It is known that carbon monoxide is practically non-existent in Titan; so, it was concluded early on that the moon's atmosphere is composed primarily of molecular nitrogen (96.4%), together with methane (less than 5% content) that had been discovered by Kuiper. These data allowed further predictions to be made, as will be seen below.

From what is known at present about the constitution of dense clouds of gas and dust that create solar systems, it is assumed that the carbon and nitrogen elements of the cloud that gave birth to our solar system would be mainly in the form of carbon monoxide and molecular nitrogen. To explain the presence of methane on Titan it is accepted that, at a given stage in the formation of Saturn and its satellites, the carbon dioxide would have reacted with hydrogen to yield methane and water. Like all other bodies of the Solar System, Saturn and its satellites formed by aggregation (accretion) of small particles, called planetesimals, consisting mainly of water ice and silicates. It is not difficult to imagine an increase in temperature in regions of pre-solar clouds caused by numerous shocks of planetesimals during the formation of Saturn. Warming would facilitate chemi-

2 Da = dalton, mass measuring unit; 1 Da is equal to 1/12 the mass of the atom of the isotope 12 of carbon.

Fig 125
Artist's image of the spacecraft "Voyager 1".
Credit: NASA, JPL.
URL: http://voyager.jpl.nasa.gov/image/spacecraft.html

cal reactions, even with hydrogen. This element is very abundant in the Universe, but because it is very light, it is usually scattered. However, the very strong gravitational field of the large planets during their formation is likely to have produced an increased density of hydrogen in their vicinity, and subsequent chemical reactions would have transformed carbon monoxide into methane and probably nitrogen into ammonia.

Of the various structures that ice crystals can adopt, the most common is a hexagonal honeycomb structure, which has the feature of trapping small gas molecules, such as those of methane and ammonia. The existence of this type of chemical association was previously mentioned in the form of "methane hydrates" in the depths of submarine hydrothermal vents. It is therefore likely that much of the methane and ammonia generated as explained above have been trapped in water crystals in the form of these complex structures, known chemically as "clathrates". During the formation of Titan by gradual accretion of planetesimals, as the amount of accreted material increased, so did the pressure exerted on it by the upper layers. Under the action of pressure and with simultaneous increase in temperature of the interior, these clathrates would be destroyed, thereby releasing into the atmosphere the methane and ammonia gases initially trapped in processes of cryovolcanism.[3] Titan does not have a magnetic field and sometimes orbits beyond Saturn's magnetosphere, so it is directly exposed to the ionizing solar wind, which removes some molecules of the upper atmosphere. Under the action of solar and cosmic radiation the above compounds are unstable and decompose. This is particularly true of ammonia, which quickly dissociates into nitrogen and hydrogen, both in the molecular form, with masses of 28 and 2 Da, respectively. Even at very low temperatures, both of these materials remain in the gaseous state, but owing to its small mass, hydrogen is lost by depletion and the much heavier nitrogen is retained.

3 Cryovolcanoes are literally volcanoes in celestial icy bodies whose magma is usually water and gas.

Though gaseous methane is more stable than ammonia, it is subject to dissociation, losing irreversibly one to four hydrogen atoms, irreversibly because, as explained above, this gas once formed depletes rapidly. The remaining species are highly reactive and recombine to give rise to hydrocarbons of varying complexity, mainly ethane ($H_3C\text{-}CH_3$), ethylene ($H_2C{=}CH_2$) and acetylene (HCCH). The nitrogen compounds, including ammonia, are also involved in analogous reactions, from which they form amines, imines and nitriles[4] (e.g. hydrogen cyanide, HCN). Just as ammonia decomposes easily into molecular nitrogen and hydrogen by dissociation of N-H bonds, amines and imines (from which $H_3C\text{-}NH_2$ and $H_2C{=}NH$, respectively, are the simplest ones) contain such links and therefore break down easily. This is not so with the cyanides (of which HCN is the most simple and abundant); so, while this species is often detected, the others are not. Experiments in the laboratory with these compounds show that, under the action of UV light, they co-polymerize to give hydrocarbons more complex than those mentioned and derivatives containing nitrogen atoms; such materials are named "tholins". They are solid, even at fairly high temperatures, and have a brownish orange color, the color observed in this moon of Saturn. This leads one to assume that these materials should be plentiful on the planet, in the form of aerosols.[5] Overall, one is led to believe that Titan may resemble the Earth as it existed just after its formation, an 'early Earth' preserved in a cold place; this is exactly why it has been and continues to be the object of great curiosity within the scientific community.

Titan has seasons, each lasting seven and a half terrestrial years, since Saturn takes thirty years to complete one orbit around the Sun. At the low temperatures common in this region of the Solar System the more complex compounds of carbon formed from methane are liquids or solids. Evaporation will occur during the hot season, whereas the liquids would condense in the form of rain during the cold season, possibly producing lakes or seas. At these temperatures, methane can exist in equilibrium between its liquid and gaseous states, in which case it is likely that during the cold season, part of the methane in the atmosphere will also condense and precipitate in the form of rain. This probable methane cycle would resemble, at least in part, the water cycle on Earth. Because hydrogen is inevitably depleted, the compounds resulting from the constant dissociation of methane cannot replace this compound and so it should have disappeared long ago from the atmosphere of Titan. For it to continue existing in the atmosphere, as discovered by Kuiper, it must be being constantly replenished, which suggests the existence of cryovolcanoes fuelling the atmosphere with methane from the interior of the planet, in a continual process of decomposition of "clathrates" and subsequent degassing. Amongst other hydrocarbons likely to be formed from methane at temperatures expected around the surface of Titan, acetylene is a solid and less dense than liquid methane. Thus, if by chance there are any lakes or seas of light hydrocarbons, blocks of acetylene and other compounds may float on them as if they were icebergs!

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4 Amines, imines and nitriles are compounds characterized by containing the groups $C\text{-}NH_2$, $C{=}NH$ and CN, respectively.

5 Droplets of a solid or a liquid dispersed in a gas.

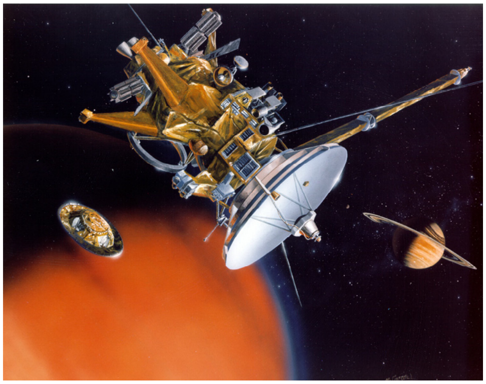


Fig. 126
Mission “Cassini-Huygens” to Saturn and Titan.
Credit: NASA, JPL.
URL: http://www.jpl.nasa.gov/images/cassini/p45424-browse.jpg

13.3 What is known about Titan

EARLY ON THE SCIENTIFIC COMMUNITY wished to know the nature of the surface of Titan. One of the strong reasons for doing so was to confirm whether or not there were oceans present where, according to some more recent models, the existence of Life would be a strong possibility. In mission “Cassini-Huygens” (Fig. 126) NASA and ESA joined together to explore the system of rings and moons of Saturn. This mission consisted of two modules, one being the ESA’s “Huygens”, to investigate the composition of the atmosphere and surface of Titan, and to collect images and scientific data during its descent and for shortly after reaching the surface. NASA’s module “Cassini”, with participation of the Italian Space Agency, was intended to remain in the orbit of Saturn, observing the atmosphere and composition of Saturn, and the geological history of its rings, in addition to establishing radio contact of “Huygens” with Earth. After seven years of travel, the orbiter “Cassini” in June 2004 entered its orbit and immediately began sending data to Earth, including radar contributions to the mapping of Titan. In October it was at 1200 km from the planet, which allowed it to obtain many high resolution images. Six months later, the probe “Huygens” was ejected and twenty days later, in January 2005, it entered the thick atmosphere of Titan. During the descent, the probe failed to detect the position of the Sun, and although it was possible to obtain images of the surface, the scientific experts said such a process was like photographing asphalt dust. It therefore seems unlikely that Saturn is visible from the surface of Titan. On reaching the surface, “Huygens” communicated for a few minutes with the module “Cassini”, which relayed the information to Earth.

Titan's features [1]

Orbital features		Mass	1.3452×10^{23} kg
Major semi-axis	0.008 167 7 AU	Average specific weight	1.8798 g cm^{-2}
Orbital circumference	9.553 AU	Equatorial gravity	1.352m s^{-2} (0.14 G)
Eccentricity	0.0288	Sidereal day	15 d 22 h 41 m 27 s
Period of rotation	15.945 d	Escape velocity	2.639 km s^{-1}
Average orbital velocity	5.58 km s^{-1}	Albedo	0.23
Tilt	0.348 54º [2]	Average temperature	–179.45 ºC
Physical features		**Atmospheric features**	
Equatorial diameter	5152 km	Atmospheric pressure	1.46 atmospheras
Surface area	8.3×10^7 km^2	Nitrogen / Methane	98.4% / 1.6%

[1] URL: http://en.wikipedia.org/wiki/Titan_(moon) [2] In relation to Saturn's equator.

This mission was designed to test every hypothesis that was raised when the composition of Titan's atmosphere was first discovered, as described above. Consequently, the probe 'Huygens" was equipped with all the tools needed to obtain answers to these many questions. Its equipment comprised an aerosol collector and pyrolyzer (ACP), a spectral and imaging radiometer to operate during the descent (DISR), a Doppler system for measuring winds during descent (DWE), a gas chromatograph coupled to mass spectrometry (GCMS) for chemical analysis of the atmosphere, a tool for analyzing the structure of the atmosphere (HASI) and a surface scientific equipment set (SSP).

During its descent winds were detected in the direction of the planet's rotation with a maximum speed of 430 kilometers per hour, decreasing in intensity as the probe approached the surface. Also during the descent temperatures, pressures and electrical conductivity of the atmosphere were measured, but no traces of lightning and thunder were found. Aerosols were detected rising into the atmosphere at an altitude of 200 km and methane clouds at 20 km above the ground. Aerosols result from decomposition of methane in the upper atmosphere, forming various organic molecules and resemble the smog found in large cities on Earth, but in this case it is much thicker; an opaque orange mist rises from Titan up to a height of 300 km and makes it difficult to observe its surface (Fig. 127), in such way that only the images taken by probe "Huygens" at an altitude below 25 km had some clarity. The atmosphere is composed mainly of molecular nitrogen (over 90%), with 3% methane in the form of mist, trace amounts of argon, water and at least a dozen other compounds such as carbon dioxide and hydrogen cyanide (Fig. 128). Amongst compounds detected in the soil that did not show up in the atmosphere were ethane and cyanogen.[6] This difference suggests a complex chemistry both on the ground and in the atmosphere. It has already been mentioned that the isotopic compositions of carbon

6 Cyanogen is a compound with two carbon atoms and two of nitrogen (NC-CN).

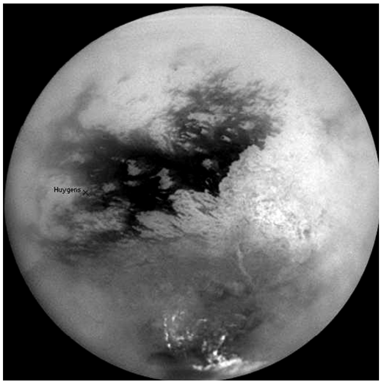


Fig. 127
Titan photographed in January 2005 by mission “Cassini-Huygens”.
Credit: NASA, JPL, Space Scienc Institute.
URL: http://en.wikipedia.org/wiki/File:Titan2005.jpg

and nitrogen on Earth do not have the same values as in the rest of the Universe. This difference, called isotopic fractionation, is affected by the existence of Life. The $^{12}C/^{13}C$ isotope ratio measurement in Titan suggests a constant replenishment of methane in the atmosphere, but no evidence of biological influences was found. The ratio $^{14}N/^{15}N$ found

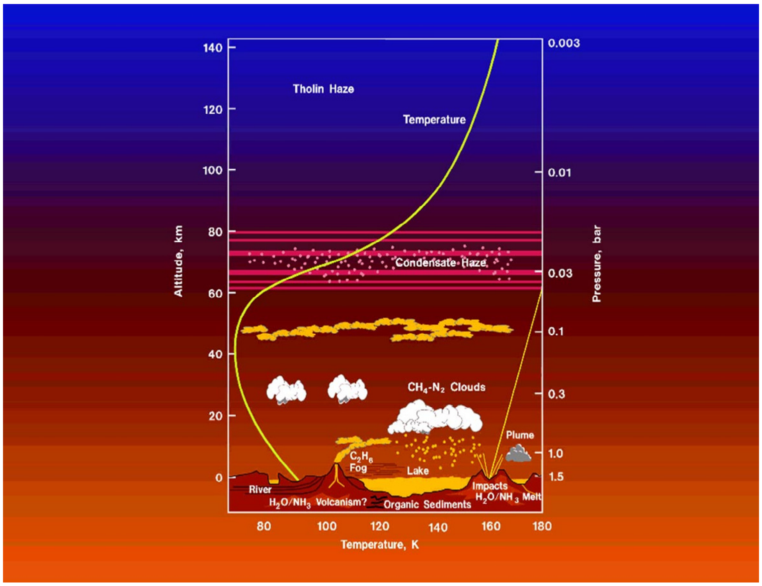


Fig. 128
Model of Titan’s atmosphere.
Credit: JPL, NASA.
URL http://en.wikipedia.org/wiki/File:Titan_atmosphere_detail.svg

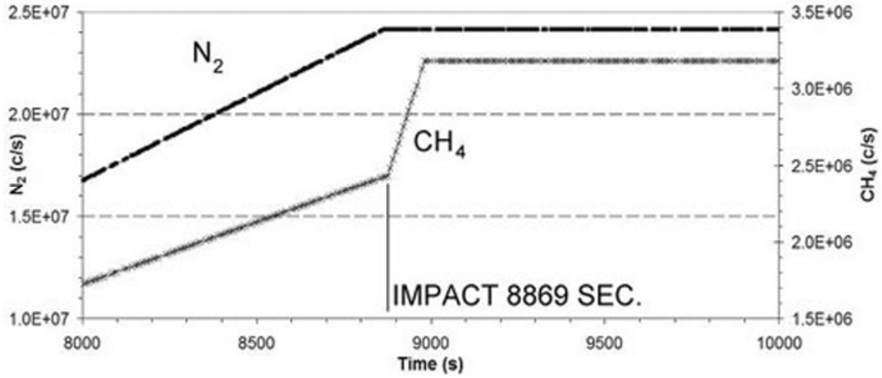


Fig. 129

Increase of nitrogen (N_2) and methane (CH_4) content during the descent of probe "Huygens" and rapid increase in methane concentration at the time that the probe touched the ground.

Credit: ESA, NASA/JPL-Caltech, GSFC, ASI, GCMS Team.

URL: http://spacespin.org/article.php/hyugens-1-composition-measurements

suggests that the earlier atmosphere of Titan must have been five times denser than today and, therefore, has been losing nitrogen to the space. Given the abundance of water in the moon, one would expect to find also a significant amount of argon. This has not happened, since the measured abundance of this noble gas was unusually small. The predominance of atmospheric nitrogen suggests that this atmosphere was initially condensed or captured in the form of ammonia. Moreover, since water is an efficient carrier of noble gases, its very large abundance in Titan is at odds with the fact that neither xenon nor krypton were detected; this unexpected result needs explanation and reflection on how Titan's atmosphere evolved. The temperature measured at the surface was about 93 K (–180 ºC) and the pressure was one and a half times that of Earth. This high pressure is mainly due to the low temperature, since the collisions between the gas molecules are not sufficient to accelerate them to or beyond the velocity of escape. Sunlight takes eight terrestrial days to reach Titan's sky, and its very thick atmosphere does not allow more than a penumbra on the surface of the planet.

At the time the probe "Huygens" hit the ground, a burst of methane was detected, probably produced by heat generated by the probe itself (Fig. 129). The place where it landed was like wet sand or soft clay with a thin hard layer on the surface. On account of the low temperatures of Titan, water can only exist as ice in the apparent form of stony banks, as shown by the images collected (Figure 130). These images revealed a diverse and complex geology, with craggy and other flat areas, and evidence of erosion at the base of the rocks, indicating possible fluvial activity. The surface consists of a mixture of water ice and hydrocarbons, and is darker than what had been anticipated. The area already mapped appears to be approximately flat and does not have any variation of altitude of more than 50 meters; however, the radar altimeter only covered part of the north polar

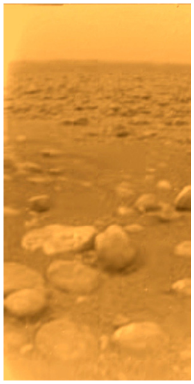


Fig. 130
Image of Titan's soil obtained by probe "Huygens". The stones that can be seen should be formed by solidified water.
Credit: ESA, NASA, JPL.
URL: http://en.wikipedia.org/wiki/File:Huygens_surface_color.jpg

region. These observations suggest that the surface is constantly renewed. Titan's soil has striped areas that seem to be caused by particles carried by the wind. The few impact craters appear to be filled, probably with rain of hydrocarbons. The images captured also revealed a complex network of narrow channels draining from the brighter uplands to the dark and flatter lower regions (Fig. 131). These channels meet in fluvial systems that

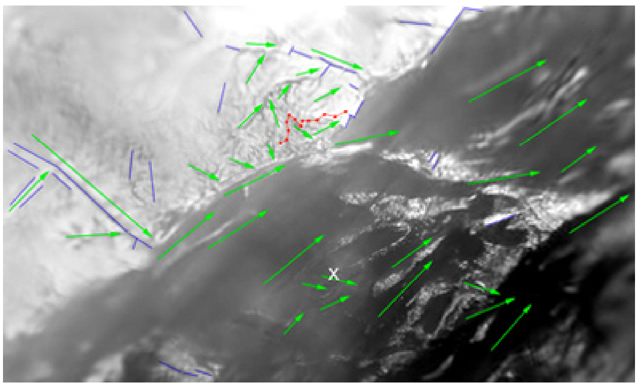


Fig. 131
Titan's surface, obtained by Huygens' DISR imager, showing patterns of tectonic and fluid-flow activity. The tectonic patterns are indicated by blue lines; the drainage divide is indicated by the red line; flow directions are indicated by the green arrows. The Huygens landing site is marked by a white cross.
Credit: ESA, NASA, JPL, University of Arizona.
URL: http://www.esa.int/esa-mmg/mmg.pl?b=b&topic=Solar%20System&subtopic=Titan%20and%20Saturn%27s %20other%20moons&single=y&start=23&size=b

flow into lakes apparently very similar to Earth. This morphology strongly suggests the existence of rivers and lakes in Titan, which at present seem to be dry, because no liquids were clearly detected. In fact, radar was used to measure surface reflectivity. An ocean of methane would not reflect more than 10% of the received signal, but the measured values are much higher, similar to those characteristic of the icy moons of Jupiter and the polar caps of Mars, and reveals a surface composed of ice. Still, liquid methane and ethane may infiltrate through cracks in the existing ice and form deep reservoirs, just as on Earth rainwater generates groundwater. In any case, under the conditions of temperature and pressure measured on the ground, methane is liquid; so, in the past it could have formed rivers and lakes. At the present dissociation rate, only 10 million years would be enough to decompose all methane in the atmosphere. As the age of the Solar System is about 4.6 Gyr, a reservoir of methane would have to exist under the surface to replenish the atmosphere. The images collected confirm this possibility, showing that at least in a past of a few million years there has been liquid on the surface. However, it could be that the formation of rivers and lakes is a periodic phenomenon and that the mission probe has reached the satellite in the "dry season". Moreover, so far only a small part of Titan has been observed

It was initially planned that the orbiter "Cassini" should continue to operate for four years, i.e. until mid-2008, with about seventy orbits to Saturn. The data received seem to confirm the possible existence of liquid water as groundwater in the polar regions of Titan. All data collected in mission "Cassini-Huygens' help to provide better understanding of the physical and chemical media that may have existed on Earth shortly after its formation. But now new avenues open up for future research. Indeed, during the mission

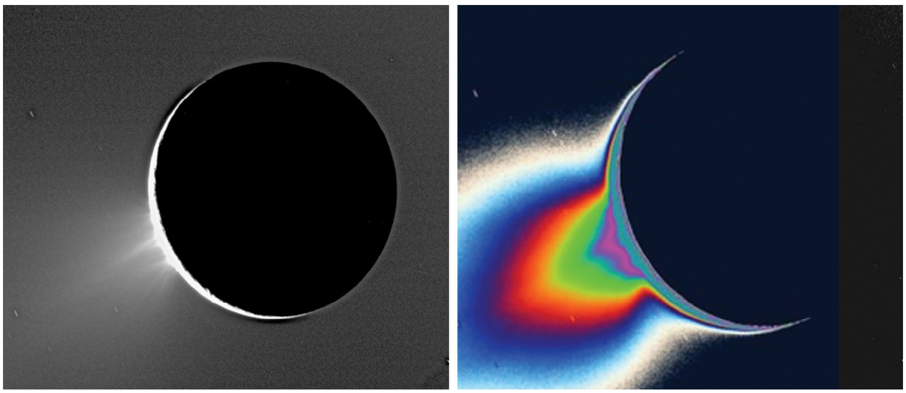


Fig. 132
Plumes of water vapor of cryovolcanic nature, in Enceladus, the second largest Saturn moon.
Credit: NASA, JPL, Space Science Institute.
URL: http://ai.jpl.nasa.gov/public/home/chien/spAGU2006Images.html and
http://www.jpl.nasa.gov/images/cassini/2005-12-06/pia07759-250.jpg

spacecraft "Cassini" has been several times close to the sixth largest satellite of this planet, the icy moon Enceladus. In these passes the instruments recorded the occurrence of ice jets and high plums, ejecting large amounts of particles at high speed (Fig. 132). In these geysers, located in a confined region of the south pole, water dominates, with significant amounts of carbon dioxide and methane. Evidence was also detected of internal activity below the region where the jets are observed. These results make Enceladus the third body known, after Earth and Io, that is sufficiently geologically active for its internal heat to be detected remotely with instruments provided with sensors. At present it is believed that such jets might come from areas close to pockets of liquid water that cannot be more than 10 meters below the surface. The region where Enceladus orbits its mother planet, in the densest part of the E-ring of Saturn, contains oxygen that is supposed to result from photodissociation of water expelled by this moon. From all these observations, the enthusiasm and expectations of the scientific community regarding the mission "Cassini-Huygens" could not be higher.

The mission has been extended until September 2010 during which time many flybys are planned to Titan, Enceladus, the icy satellite Dione and to the heavily cratered Rhea. There is much optimism that this close study of the Saturnian system will shed further light on the likely formation of planet Earth and on how Life came to be established here.

Chapter 14

The comets

The known is finite, the unknown is infinite. Intellectually, we stand on an islet in the midst of an illimitable ocean of inexplicability. Our business in every generation is to reclaim a little more land, to add something to the extent and the solidity of our possessions.[1]

Fig. 133
Comet "Halley" photographed in March 1986.
Credit: NASA, IHW, Liller Nasaw.
URL: http://en.wikipedia.org/wiki/Image:Lspn_comet_halley.jpg

COMETS HAVE BEEN KNOWN SINCE ANTIQUITY, and there are even Chinese records of comet "Halley" back to at least 248 BC. Graphic references of the same comet are also found in the famous French tapestry of Bayeux, which celebrates the conquest of England by the Normans in 1066, and Giotto di Bondone's (1266–1337) frescos in the Upper Basilica in Assisi, Italy, as well as in the famous Nativity in the Sistine Chapel of the Vatican, both dating from the early fourteenth century — Giotto saw the comet in 1301. Comet "Halley" is perhaps the most famous, not only because usually it is easily observed due to its great brightness, but also because it was the first to be recognized as a space traveller that returns regularly, a "star" with a very elliptical orbit. In 1682, Edmond Halley realized that the comet he had just observed had characteristics similar to those that had been observed by Johannes Kepler in Prague, in 1607, and by the mathematician, astronomer and cartographer Petrus Apianus in Germany, in 1531. Kepler determined its orbit and predicted that it would return in 1758, some 76 years later. And indeed it did return, but Halley did not live the required 102 years to confirm his calculations! However, in homage to this distinguished astronomer,

1 Thomas Henry Huxley (1825–1895), *in* "On the Reception of the Origin of Species", 1887.

who had supported the publication of Isaac Newton's (1642–1727) famous *Philosophiae Naturalis Principia Mathematica* ("Mathematical Principles of Natural Philosophy"), the comet was given his name. Comets then started being given the name of their original discoverers. They are the celestial objects that in the past gave rise to fears and superstitions; they were often mentioned as messengers of woes whereas the appearances of a few others were seen as good omens. In 1588, Tycho Brahe published in Uraniburg, Denmark, his work *Mundi Aether Recentioribus Phaenomena* ("On the Phenomenon of the Ethereal World"), where he described his observations made during the 1577 appearance of the comet; this was more than a century before Halley finally interpreted the phenomenon whose origin and nature neither Brahe nor his friend Kepler had even glimpsed. However, ten years earlier, in 1578, the Portuguese physician and philosopher Francisco Sanches (1551–1623), professor at the University of Toulouse, France, and a precursor of René Descartes, had published his poem *Carmen de Cometa Anni MDLXXVII* ("Song of the Comet the Year 1577"), where he demystified this "phenomenon of the ethereal world", stating that "natural things are explained by natural causes". Sanches could not have imagined that four hundred and nine years later, in 1987, the world would be watching not so much the comet "Halley", that appeared again, but the probe "Giotto" that the ESA in Toulouse sent into space to meet 'Halley' in order to observe it very closely. History is written in circles...

14.1 The nature of comets

CLASSICALLY COMETS ARE DESCRIBED AS being composed of a "head", a "coma" and a "tail" (Fig. 134). It is now known that the "head", also known as the core, is largely

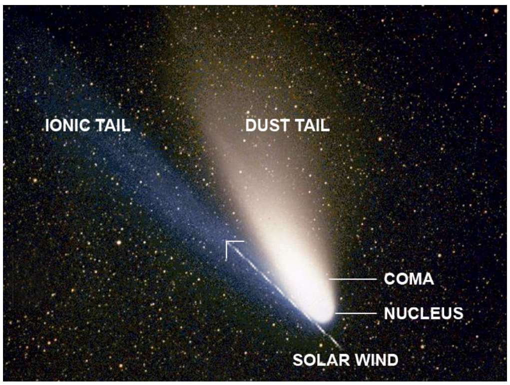
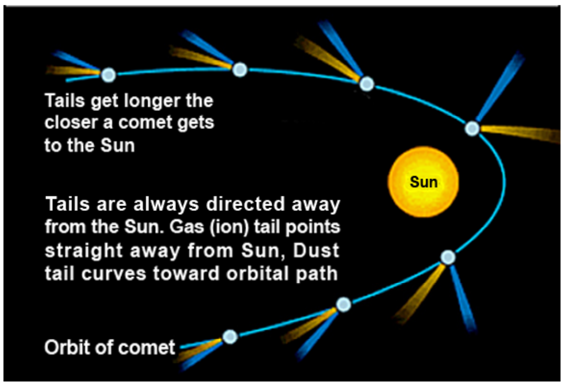


Fig. 134
Visible parts of a comet.
Photograph of Hale Bopp comet by Geoff Chester, Blackwater Falls State Park, Davis.
URL: http://pt.wikipedia.org/wiki/Ficheiro:Halebopp031197.jpg

composed of carbon dioxide ice, methane, ammonia and water, mixed with dust and various mineral aggregates covering a possible central rocky component. For this reason, they are often referred to as “dirty snowballs”. When approaching closer than the orbit of Jupiter, the Sun’s heat vaporizes the ice, creating a cloud around the nucleus, which is now called the “coma”. The solar wind projects the material in the “coma” in the direction opposite to the Sun, forming the “tail”. The sublimation of ice that is trapped in rock cavities may cause jets of gas, which tend to spread the material from the comet for thousands of kilometers and contribute to the spread the coma. The “tail” of the comet can be divided into two parts, one that can be curved and is formed by dust, and a straight part formed by electrically charged particles; both always point in the opposite direction to the Sun, whatever the position of the comet (Fig. 135).

Each time one of these bodies visits the inner Solar System it loses a significant part of its volatile material and also of its rocky material that was agglutinated by the ices. Consequently, after several appearances, all the ice, much dust and some rocky pieces are lost into space, with a dark rock remaining. The above materials released by comets are primarily responsible for the meteors that fall on Earth, that are commonly known as “falling stars” or “shooting stars”, as already mentioned above. Whenever the Earth passes through a region of space that was crossed by a comet, one is presented with the dazzling spectacle of “falling stars”.

One of the classifications of comets divides them into two categories; those with lapses between consecutive appearances of less than 200 years are called short period comets, the remainder being called long-period comets. The vast majority of comets orbit the Sun at such a distance that, although they are attracted by its enormous gravitational force, they pass by the star; if it were not so, nearly all of them would have been destroyed



Fig, 135
Direction and size of comet tails.
Credit: NASA.
URL http://upload.wikimedia.org/wikipedia/commons/a/a9/CometDiagram.gif

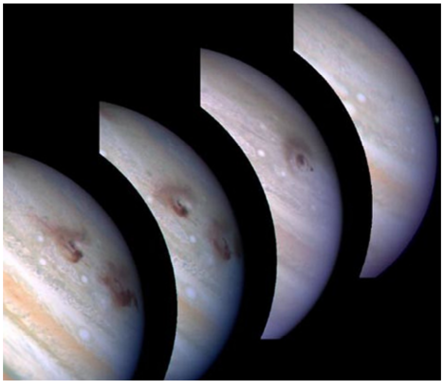


Fig. 136
Successive images of Jupiter showing the "scars" caused in the dense atmosphere of the planet by the fall of fragments resulting from the breach of comet "Shoemaker-Levy 9" in the summer of 1994.
Credit: H. Hammel (MIT), WFPC2, HST, NASA.
URL: http://apod.nasa.gov/apod/ap980804.html

during the 4.6 Gyr existence of the Solar System. Occasionally, gravitational interaction with the planets may change their orbits and lead them to destruction, with the Sun or with any planet, particularly the gigantic planets Jupiter and Saturn. The disaggregation and impact of the debris resulting from comet "Shoemaker-Levy 9" on Jupiter in the summer of 1994 was undoubtedly one of the most spectacular effects observed to date with a comet (Fig. 136).

Comparing the information recorded over the years on the orbital characteristics of many comets, the Dutch astronomer Jan Oort (1900–1992) found that none of them had an open orbit (parabolic or hyperbolic), which would indicate that they come from outer space. He also found that, besides having elliptical orbits, the long period comets have aphelions (greatest distances from the Sun) which showed values of the order of 30,000 AU. As a result of these findings, Oort in 1950 suggested that long period comets come from a region of space that contains the Solar System and would be situated at the above distance from the Sun. His calculations indicated that this region would contain approximately 1012 potential comets with diameters larger than 1.3 kilometers, the total mass corresponding to about half of that of the Solar System. This "theoretical" region is now known as the "Oort Cloud" and is known to begin beyond the previously mentioned Kuiper Belt (see section 13.1), at a distance of about 50 AU from the Sun, extending up to 125,000 AU. In contrast, the short-period comets should come from the "Kuiper Belt", which begins beyond the orbit of Neptune, at about 30 AU from us, and extends up to the "Oort Cloud". It is estimated that it can accommodate about 35,000 bodies larger than 100 km. The "Asteroid Belt", which lies between the orbits of Mars and Jupiter is made up of remnants of the cloud of gas and dust that created the Solar System and that, as a result of a gravitational perturbation within this region, never gave rise to a planet;

moreover, all matter contained in the Belt would be sufficient for a planet the size of Earth. Also, the bodies existing in both the "Kuiper Belt" and the "Oort Cloud", including eventual planetesimals and asteroids, are material objects that did not coalesce into planets when the Solar System was formed, i.e. they are debris left over from condensation of the pre-solar cloud. Not only are these remains very old, they are retained at distances remote from the Sun, at temperatures close to absolute zero and protected from the sunlight that otherwise would destroy much of the chemical material of which they are composed. For this reason, comets are presently of great interest as testimonies of the history of the Solar System, and as a reservoir of chemical matter that would have existed here when our planet was formed, and of the matter that continued bombarding the Earth during the early stages of its evolution when it was inhabited by the first living beings.

14.2 The first cometary missions

THE PREVIOUSLY MENTIONED PROBE "GIOTTO" (Fig. 137) was sent into space in early July 1985 and just over eight months later it was within 596 km of comet "Halley"; in astronomical and astronautical terms this distance is very small, small enough to enable the collection of much detailed information. Indeed, the first high-resolution images of a cometary nucleus were obtained and significant amounts of various materials identified, such as carbon monoxide, carbon dioxide, methane and traces of other hydrocarbons, as well as iron and sodium. Two main classes of particles were found, one class being dominated by light elements such as carbon, hydrogen, oxygen and nitrogen and the other with minerals rich in elements such as sodium, magnesium, silicon, iron and calcium. It should

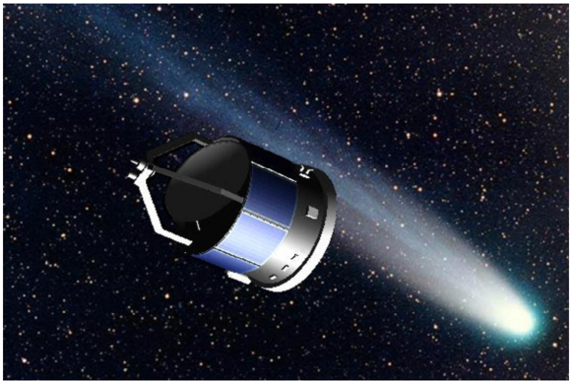


Fig. 137
Artist's representation of European Giotto spacecraft approaching comet "Halley".
Credit: Andrzej Mirecki.
URL: http://en.wikipedia.org/wiki/File:Giotto_spacecraft.jpg

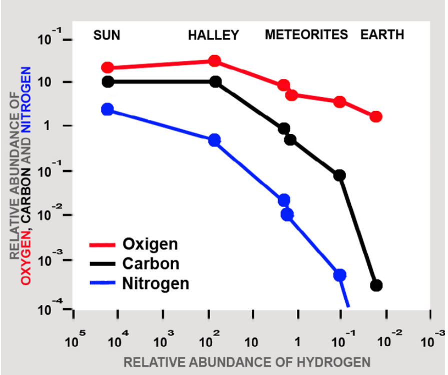


Fig. 138

Plot of the relative abundance of biogenic elements (O, C, N) against to the relative abundance of hydrogen (relative abundances are in turn referred to silicon).

According to data of the European Space Agency in URL http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=37409

be noted that the light elements, excepting nitrogen, were found in the same proportions as exist in the Sun, which means that comet "Halley" is composed of the most primitive material known in the Solar System (Fig. 138). Surface features (craters, ridges and mountains) were observed together with "emitting vents", places where gas plumes are ejected. The structures of the coma were discovered and the gaseous components comprising atomic, molecular, radical and ionic forms were analyzed *in situ*. It was confirmed that water is by far the most abundant constituent (about 85%) of the gas phase. It was also learned that the nucleus of comet "Halley" is the darkest object known in the Solar System, darker than coal, with an albedo of about 0.03, and that its density is as low as 0.1 — which implies that it is porous.

Comet "Halley" has also been observed by two probes of the Japanese space agency (ISAS), the "Sakigake" and "Suisei" (terms that mean "pioneer" and "comet", respectively). The first passed at 7,000,000 km and the second at 151,000 km of comet "Halley". In 1984 the USSR had two spacecraft sent into space, "Vega 1" and "Vega 2", with the aim to launch two probes at planet Venus. After this mission was terminated, both probes were redirected in order to intercept the comet; this was successfully achieved in March 1986, with an interval of three days. The first craft passed at a distance of 10,000 km and the second at 3000 km from the comet. Around the same time a wider operation was established for observation and collection of data from the Earth, and named "International Halley Watch (IHW). Having fulfilled its mission, the American probe "International Sun-Earth Explorer-3 (ISEE-3), which had been in space since the early 1980s studying the Sun, began in 1982 to be carefully redirected at the expense of some of its remaining fuel and gravitational impulses from the Moon, to the comet "Giacobini-Zinner". This target was achieved in September 1985 by which time the name of this NASA's spacecraft had been changed to "International Cometary

Explorer" (ICE). Its mission was completed when in March 1986 it also passed in the track of comet "Halley", where some additional measurements were made. It was about this time that the disaster occurred to the shuttle "Columbia" during its flight to the comet. These were the first space missions prepared for observation of a comet. Given its close encounter with comet 'Halley', the "Giotto" mission was inevitably the one that gathered more information.

In 1998 NASA launched the spacecraft "Deep Space 1" in order to observe the asteroid "Braille "and then comet "Borrelli"; as planned, it passed the latter target in September 2001 at a distance 2171 km and at a relative speed of 16.58 km s^{-1}. An instrument combining a device for obtaining images of visible light with UV and IR spectrometers obtained images and other data about the comet.

14.3 The "Stardust" mission to comet "Wild 2"

IN 1999 NASA LAUNCHED A NEW COMET mission, the "Stardust" (Fig. 139), in order to obtain high-resolution images of the nucleus, and especially to collect and send to Earth at least 1,000 samples of coma dust and gas of a comet with a size of 5.4 km, "Wild 2", discovered in 1978 by Swiss astronomer Paul Wild, of the University of Bern. Although these samples were intended to be analyzed with regard to elementary, isotopic, mineralogical, chemical and biogenic properties in Earth laboratories, the spacecraft was also equipped with instruments to conduct analyses *in situ*. In December 2003 it penetrated the coma and in January 2004 was at a closest approach distance of 250 km from the nucleus. In mid-January 2006 a capsule containing the collected

Fig. 139
Artist's representation of spacecraft "Stardust" on its way to comet "Wild 2".
Credit: NASA.
URL: http://science.nasa.gov/headlines/y2003/31dec_stardust.htm

Fig. 140
Olivine mineral brought to Earth by mission "Stardust".
Credit: NASA, Ames Research Center.
URL: http://www.sti.nasa.gov/tto/Spinoff2006/r_d.html

samples was separated from the spaceship and sent to Earth, where it was received shortly after. The spacecraft was left in hibernation in a solar orbit, charging batteries for future missions. Comet "Wild 2" appeared recently in the inner Solar System, which means this is a relatively "fresh" body, i.e. it was neither heated nor degassed by the Sun. Analysis of the collected material revealed that some of it, namely the mineral olivine (Fig. 140), was formed under heat and pressure, which indicates a location very close to the Sun or another star, instead of the most remote and cold regions from where comets usually originate.

Should it be confirmed, this finding will challenge the current view about the formation of the Solar System, namely that the lighter constituents (such as the gases that formed the gas giant planets) would have been depleted to the most remote regions right at the start of its formation, while the heavier materials would have remained close to the star. Olivine, a green mineral that is present in the composition of rocks on our planet, is formed in media with temperatures of about 1100 °C and consists essentially of iron and magnesium, together with other elements such as calcium, aluminum and titanium, all of them "refractory minerals". Thus, its presence in "Wild 2" leads us to rethink our conception of the early Solar System; in fact, it provides a stronger emphasis to a model that predicts that strong jets of solar wind, coming from the star under rotation, may be the cause of cometary nuclei being thrown to more distant regions, at the edge of the Solar System where currently they exist. Everything now seems to indicate that comets are made of a mixture of materials formed in a wide range of temperatures, in places ranging from very near to the primitive Sun to very remote places. The latest published results suggest that the comet is composed of a mixture of materials generated in our Solar System with grains of materials that may come from other stars. However, the results are still under consideration.

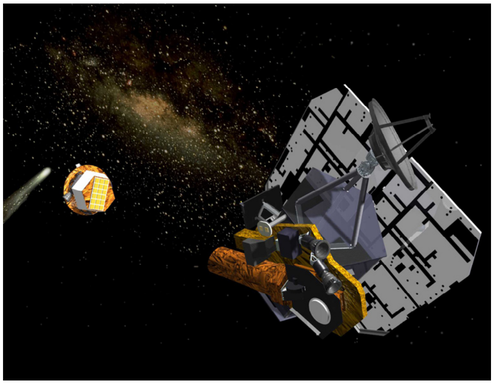


Fig. 141
Artist's representation of "Deep Impact", showing on left the projectile dropped on "Tempel 1".
Credit: NSSDC, GSFC, NASA.
URL: http://nssdc.gsfc.nasa.gov/planetary/image/deep_impact_comet.jpg

In mid-2001 NASA sent a new mission into space, called "Genesis", this time not to observe a comet, but to collect samples of solar wind in order to compare its composition with that collected by "Stardust". At the end of the year the collection began and in the following Spring the five month return journey commenced. The capsule containing the samples was released on schedule, but, because the parachute designed to cushion its fall on Earth failed to open, it entered into free fall at a speed exceeding 300 kilometers per hour. However, the fragments of the capsule were collected in an attempt to salvage some of the information that had been collected.

14.4 The "Deep Impact" mission to comet "Tempel 1"

At the start of 2005 the launch of a cometary research mission named "Deep Impact" (Fig. 141) was initiated. Its main objective was to send a projectile carried by the spacecraft to impact the comet in order to analyze the primitive materials from the comet's interior. The comet chosen was "Tempel 1", discovered in 1867 by the German astronomer Ernst Tempel (1821–1889) which has a period of 5.51 years and an orbit with a major semi-axis of 3.12 AU. The projectile was a copper and aluminum cylinder weighing 370 kg, fitted with a self-propelling system to travel at a speed of 90 kilometers per hour and with self-orientation instruments; it included a camera that was supposed to operate until the moment of impact (Fig. 142). When this occurred, the spacecraft was located at 10,000 km from the core, and ten minutes later, now at the distance of only 4000 km, observations began, lasting just over a minute, of the impact crater thus formed; two minutes later the spacecraft had reached its distance of closest approach, 500 km, at which point it diverted

Fig. 142
Image of the impact between module SMART and comet Temple taken with the Deep Impact's high resolution camera 69 seconds after the impact.
Credit: NASA.
URL: http://en.wikipedia.org/wiki/Image:Deep_Impact_HRI.jpeg

automatically from its path in order to gain protection from dust that was ejected.

The data collected show that, at least in the first tens of meters depth, the comet is extremely fragile, with no signs of the existence of a solid layer. This means that instead of being composed of large chunks of rock and ice, "Tempel 1 is made up of very small and thin grains kept together only by gravity. This illustrates, once again, a change in the way comets have until recently been envisaged. With regard to their surface properties, the low density and porosity should now be emphasized (75–80% of the core is empty space). The observations that revealed their evolution were the lack of volatile elements near the surface, the existence of a porous surface and the presence of different surface levels and of impact craters. While covering only about 0.5% of the comet, ice was found; it should be emphasized that this was the first time that water ice had been found on the surface of a comet. However, the small amount of ice observed was not sufficient to produce much detected water and its by-products in the coma. It was therefore concluded that there will be water beneath the surface of the comet contributing to the coma. Another important aspect is that the particles of water ice are larger than the ice grains in the coma, which suggests they are possibly the result of condensation on the surface of the comet. Probably "Tempel 1" is not a primary block of cometary material, but a fragment, which should therefore more properly be called a cometesimal. Results of IR spectroscopy show an asymmetric distribution of water vapor and of carbon dioxide in the coma (Fig. 143). The abundance of water is greater on the side of the Sun, where solar radiation sublimates the ice; also carbon dioxide is more abundant in the southern hemisphere of the comet; these data suggest that the composition of the comet's nucleus is heterogeneous. As one of the main objectives of the mission was to ascertain whether this nucleus has a uniform composition, the answer was found to be negative. The detailed study of these coma

asymmetries provides insight into the relative abundances of the molecular components that are dominant in the internal coma and in regions that are sources of degassing of volatile material that make up the anisotropic core, and also into the formation and evolution of the core.

The expectation in this mission was that in 2005, telescopes in 35 Earth observatories, in addition to those based in space, would work together in the collection and interpretation of as much data as possible. The dispersion spectrometer of the telescope of the W.M. Keck Observatory, located on the dormant volcano Mauna Kea, in Hawaii, captured spectra of eight gases in the material ejected by the impact, i.e. water, ethane, hydrogen cyanide, carbon monoxide, methanol, formaldehyde, acetylene and methane. Of these compounds, only water, ethane, methanol and hydrogen cyanide were measured before and after impact; after impact, the abundances of methanol and hydrogen cyanide were unchanged, while that of ethane had more than doubled. Carbon monoxide, methane and ethane have low sublimation temperatures; so, probably they will be the least abundant components of the core.

Other important information was collected by the Spitzer Space Telescope with its IR spectrometer, which revealed the signatures of various minerals that must have been the main components of the primordial material of planets, comets, and other bodies in our solar system. These were clays, iron-containing compounds, carbonates (the minerals in seashells), crystallized silicates (such as the green olivine minerals found on beaches and in the gemstone peridot) and polycyclic aromatic hydrocarbons (PAHs) (Fig. 143).

Another important goal of this mission was to find the difference between the surface

Fig. 143
The various minerals that must have been the main components of the primordial material of the Solar System: ice and dry ice (on plates, from left to right); olivine, smectite clay, polycyclic aromatic hydrocarbons, spinel, metallic iron (in measuring cups, from left to right); the silicate enstatite, the carbonate dolomite, and the iron sulfide marcasite (on table in the front, from left to right).
Credit: NASA, JPL.
URL: http://deepimpact.jpl.nasa.gov/images/results-regionalspectra.jpg

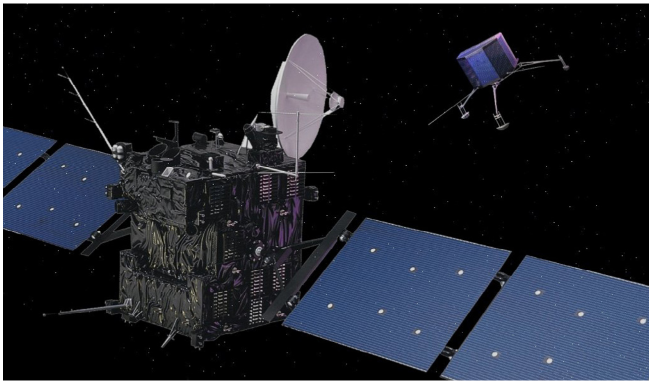


Fig. 144
Artist's representation of spacecraft "Rosetta" on its way to comet Churyumov-Gerasimenko, showing on the right the lander module "Philae".
Credit: NASA, NSSDC, GSFC.
URL: http://nssdc.gsfc.nasa.gov/image/spacecraft/rosetta.jpg

composition of "Tempel 1" and that of its interior. To achieve it, the team members of mission "Rosetta", to be described below, analyzed the formation of cyanogen radicals (CN). This radical is produced when a more complex molecule — cyanogen (C_2N_2) or, more likely in this case, hydrogen cyanide, appropriately called the "mother molecule" of the radical CN — decomposes. The results thus obtained suggest that there was a larger amount of "mother molecules" of CN in the cloud produced by the impact than there was in the coma before impact. Such a result could mean that while the normal emission of gases from the comet occur near the surface, the impact "unearthed" hydrogen cyanide from deeper areas. Thus, the analysis of the material ejected by the impact showed the existence of organic matter.

Tempel 1 will be visited again in 2011 by the Stardust spacecraft as part of its extended mission. This will be the first time that a comet will have been visited twice and is an opportunity to better observe the crater that was created by Deep Impact.

14.5 "Rosetta" mission to comet Churyumov-Gerasimenko

As any one comet approaches the inner Solar System, sublimation of its volatile compounds, followed by interaction with the solar wind, leads to its partial decomposition and conversion into new and simpler compounds that later are observed in its coma and tail. There is no direct evidence of the chemical composition of the nucleus; one can only assume that the molecules detected in the tail come from their precursors in the nucleus. However, many organic compounds, including those of biological interest, can never be detected in the coma, some because they are non-volatile, such as amino acids, and others because they decompose by the action of the solar winds or even by the energy

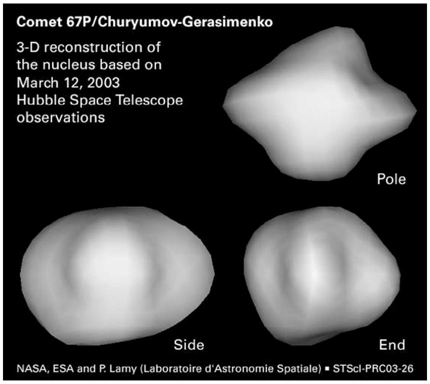


Fig. 145
Three-dimensional reconstruction of the core of comet "Churyumov-Garasimenko", based on observations of the 12th of March 2003 by the Hubble Space Telescope (HST).
Credit: NASA, ESA, Philippe Lamy.
URL: http://hubblesite.org/newscenter/archive/releases/2003/26/

released by the interaction as in the case of mission "Deep Impact". Thus, it would be appropriate to schedule a mission for a "rendezvous" with a comet in a place far enough from the Sun to avoid decomposition. Such a mission has been underway since March 2004 when ESA sent the spacecraft "Rosetta" (Fig. 144), for an encounter with comet "Churyumov-Gerasimenko". This comet travels between the orbits of Earth and Jupiter and will be reached in 2014 at a relative velocity of 120,000 kilometers per hour. On that date, in addition to observing the comet itself, the spacecraft module will eject a lander, called "Philae", which will land on the core and then carry out analysis in situ. The type of data to be collected by this mission will be similar to that planned for mission "Cassini-Huygens" to Titan. When travelling through the "Asteroid Belt" it will gather information on chosen asteroids. One was studied in September 2008 and a second is scheduled for observation in July 2010. The spacecraft will then enter into deep space hibernation for about four years until the time comes to start approach maneuvers. The comet "Churyumov-Gerasimenko (Fig. 145), with a period of 6.57 years, was discovered in 1969 by Klim Ivanovitch Churyumov, of the University of Kiev, Ukraine, on a photograph obtained by Svetlana Ivanovna Gerasimenko (1945–), of the Institute of Astrophysics of Dushanbe, Tajikistan. The name of this mission was chosen in honour of the famous Rosetta Stone, which was a valuable aid in deciphering the Egyptian hieroglyphs; the name of the lander module was inspired by the island of Philae in River Nile, which contains an obelisk that also aided that deciphering.

Chapter 15

Conclusion

On my return home, it occurred to me, in 1837, that something might perhaps be made out on this question by patiently accumulating and reflecting on all sorts of facts which could possibly have any bearing on it.[1]

Fig. 146
"Cosmic Composition", oil on pasteboard (1919) by Paul Klee (Bern, Switzerland, 1879–1940).
Credit: Olga's Gallery, New York, USA.
URL: http://www.abcgallery.com/K/klee/klee3.html

An article published in Newsweek in 1970 reported an unusual phenomenon, the emergence of a micro-organism in a camera that had been brought aseptically by Moon mission "Apollo 12". This camera had been left in Earth's natural satellite by NASA's mission "Surveyor 3", which landed on the Moon in April 1967. Two and a half years later, in November 1969, Charles "Pete" Conrad (1930–1999), the same pilot who had left it there, this time piloting the "Apollo 12", landed again on the Moon and

1 Charles Darwin (1809–1882), *in* "On the Origin of Species", 1859.

Fig. 147
"The Universe (The Cellular Structure of Space-Time)", bronze (2009), by Julian Voss-Andreae (Humburg, 1970–).
Courtesy of Julian Voss-Andreae, Portland, USA.
URL: http://julianvossandreae.com/work.html

brought the instrument back. With the great astonishment of those who were closely involved with the mission, between 50 and 100 bacteria of strain *Streptococcus mitis* were found in a small piece of polyurethane foam from inside the camera. They were alive and everything indicated that they had survived nearly three years of exposure to intense solar radiation, an almost absolute vacuum in a deep freeze of temperatures below –200 ºC, without water or nutrient or any source of chemical energy! *Streptococcus mitis* is a harmless bacterium that inhabits the nose, mouth and throat of humans, protecting them by competition against the growth of harmful bacteria. Being a fact that nobody could explain at the time, it ended up by being forgotten and left waiting for any eventual confirmation. A decade later hyperextremophiles were discovered and the "story of bacteria that went to the Moon and came back", returned to the spotlight and remained there for a few more years, until the facts were scrutinized by experts. The question of whether it would constitute a case of contamination was then revived, a contamination occurring when the protective bag was opened after return. Doubt has been raised for more than thirty years and the case has become known as the "Myth of *Streptococcus mitis* on the Moon". Subsequently NASA denied this event and in 2007, in order to confirm a possible breakdown of the sterilization technique, funded a project to investigate the film recordings that were made at the time. This episode illustrates the ease with which imagination can create Life beyond Earth. When the impact generated by the incredible progress of Science and Technology of our time receives a subsequent stimulus from science fiction-type events this may easily turn any skeptic into a gullible person, however expert and experienced he or she may be in their area of expertise — undoubtedly, this applies to all NASA technicians and scientists!

Fig. 148
“Primordial Matter”, sculpture by Béla Vízi (1936–), University of Veszprém (Hungary).
Courtesy of Professor Béla Vízi, University Pannonia, Veszprém, Hungary.
URL: http://www.vizibela.hu/

15.1 The environments for Life

THE SOVIET SCHOOL USED TO SPEAK OF “astrobiology” but then, in 1960, Joshua Lederberg (1926–) created the term “exobiology” to describe the scientific study of Life beyond Earth. Lederberg had received a Nobel prize for Physiology or Medicine two years before (1958), and was then responsible for the medical and biological issues related to the “Apollo” missions. Given the continued lack of evidence of Life beyond Earth, apart from that sent from our planet, this buzzword has begun to become popular as the science that deals with an “issue with no content”. It gradually started being used to describe the science that deals with the search for an explanation for the origin of Life in the Universe (whether on Earth or beyond it), mainly restricted to the post-Urey-Miller chemistry and biochemistry. However, the growing knowledge acquired over the last thirty years on extremophiles made it possible for biologists to contribute, not so much an explanation for the origin of Life, but to continue the search for the eventual discovery of Life beyond Earth. As others had appropriated the term “exobiology”, they resorted to the original Soviet term “astrobiology”, but following collaboration between the Americans and Russians in the field of Astronautics this name gained general acceptance. In 1998, NASA created the “NASA Astrobiology Institute” (NAI) as “an innovative way to develop the field of astrobiology and provide a scientific support for aeronautic missions”. The postmodern meaning of this word, as well as the purposes of this Institute are clearly defined in its website (URL: http://nai.arc.nasa.gov):

> “The mission of astrobiology is to study the origin, evolution, distribution, and future of life on Earth and in the Universe. Astrobiology shares with other space related science programs

Fig. 149
"Starry sky", oil on canvas (1888) by Vincent van Gogh
(Zundert, Netherlands, 1853–1890).
URL: http://www.book530.com/paintingpic/1226a2/-i-b-the-starry-night.jpg

a broad range of research interests. Astrobiology encompasses the understanding of biology as a planetary phenomenon. This includes how planetary processes give rise to life, how they sustain or inhibit life, and how life can emerge as an important planetary process; how astrophysical processes give rise to planets elsewhere, what the actual distribution of planets is, and whether there are habitable planets outside of our solar system; a determination of whether life exists elsewhere and how to search for and identify it; what the ultimate environmental limits of life are, whether Earth's biota represent only a subset of the full diversity of life, and the future of Earth's biota in space".

With such a comprehensive definition, a good part of Astrophysics and almost all Astrochemistry would be embraced by Astrobiology..., Additionally, it is added: "The mission of the NASA Astrobiology Institute is to further our understanding of these profound questions…"

Discounting such excesses, one cannot but see and stress here that an institution that houses so many and so highly qualified scientists as NASA no longer sees Life and its origin as an earthly phenomenon, but instead considers them as universal realities.[2] Over the past ten years, NAI has developed a visible and prominent activity in leading programs related to the investigation of the origin of Life and the search for extremophiles and hyperextremophiles, that point to the possible existence of Life beyond Earth. The requirement of our planet for extreme habitats that may resemble environments known on other planets, as presently is the case at Mars, can promote lively encounters between chemists and biologists who are interested in defining what is, ultimately, a living being. On these grounds,

2 Although NASA has funded Frank Drake's (1930–) and Carl Sagan's (1934–1996) SETI (Search for Extraterrestrial Intelligence) during the times of the cold war, possibly this was done not so much in the hope that extraterrestrial Life would be found, but in order to know more about the Soviet space adventures.

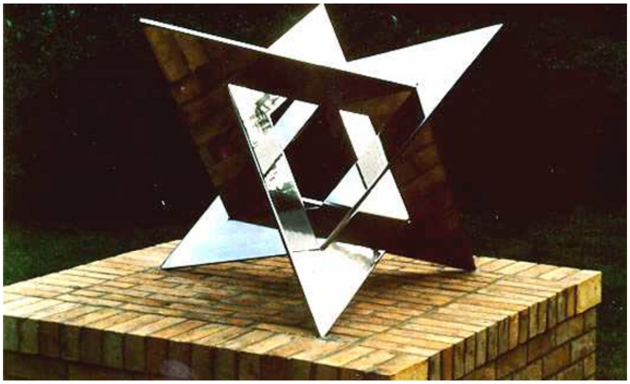


Fig. 150
"Genesis", sculpture by John Robinson (London, 1935–2007).
The Isaac Newton Institute for Mathematical Sciences, Cambridge, UK.
URL: http://www.newton.ac.uk/art/genesis.html

investigations have been carried out on the behavior and resistance of organisms on Earth under the adverse conditions of space, particularly that of microgravity. The possibility has also been tested of comets, meteorites and cosmic dust having transported biomolecules or living cells through space, as proposed by advocates of the Panspermia model. From this it follows that Life could have been generated anywhere in the Solar System and then transported from planet to planet, including ours. As new ways are discovered of Life surviving in the most inhospitable places on Earth, the possibility that this has happened elsewhere is gaining consistency and credibility. The conceptual change about the necessary conditions for Life to develop also raises an important question: Is water essential for Life? Why not another solvent, such as methane, for example? At present nothing is known about this and it is difficult to imagine prebiotic chemical reactions taking place in a solvent other than water, especially since it is so abundant. The extremophiles have also questioned our preconceptions of Life, and this leads to further questions such as: What actually is Life? What kind of life is one looking for? Under what conditions? We live in a world where there is still so much to discover. The NASA Astrobiology Institute will certainly contribute to our understanding — at least that is what they propose to do.

15.2 The search for Life

IN THE FIELD OF SPACE MISSIONS AND investigations of environmental conditions that might support Life beyond Earth, many questions remain. Regarding the study of the Moon, the American / Soviet lunar "rendezvous" only collected samples from nine sites, a tiny fraction of the lunar surface. Very little still is known about the far side of the Moon,

Fig. 151
Dry Lake in the Atacama Desert, where there was no rain for 400 years.
Photograph by unknown author.
URL: http://weblogs.sun-sentinel.com/news/weather/hurricane/blog/drought_conditions/

as well as about its poles. In the case of Mars, it is the search for Life or for signs of extinct Life that still drives the vast majority of missions to this planet, because although the results from the previous missions indicate that there is no Life, the portion of the planet explored by "rovers" or surface modules is still extremely small. In addition, these 'rovers' never explored the deep underground or polar regions, which, being covered by water ice and carbon dioxide, could possibly accommodate forms of Life known on Earth as psychrophiles or polyextremophiles. The NASA mission "Phoenix" aims precisely to explore this territory. When the same tests that mission "Viking 1" carried out on Mars were carried out in the Atacama Desert (Fig. 150) in northern Chile, the highest and driest region of our planet, the results were the same: no Life — yet there are lichens in Atacama! The results of the missions already undertaken and currently underway are similar. With the development of more modern technologies for scientific research, advances have been made regarding our knowledge of the chemical composition of the atmosphere and the planet's surface, on the variations that occur in pressure and temperature, and on the topographic morphology, amongst others. To identify traces of water on other planets, even in the remote past, has usually been regarded as the first step to finding traces of Life similar to that on Earth. The truth is that at present there is virtually no doubt that there is water on Mars, which has brought about a new sense of hope, and makes it possible to continue promoting missions to the red planet. The possible existence of an "ocean" beneath the surface of Europa encourages the deployment of new missions to this moon, and opens new horizons and possibilities of finding extraterrestrial life. Titan, and perhaps some of the other moons of Saturn, are amongst the most promising bodies to accommodate Life within our solar system, despite their most hostile environments.

Fig 152
"The Tree of Life", mural (1909) by Gustav Klimt (1862–1918).
Palace Stoclet in Brussels.
URL: http://sofachayenn.wordpress.com/2009/01/12/gustav-klimt/gustavklimt-the-tree-of-life-1909

Together with Mars and Europa, Titan is considered one of the most promising sites for prebiotic synthesis in the Solar System. Titan may constitute a natural laboratory allowing us to observe some of the crucial steps that have given rise to Life on Earth. This large satellite of Saturn continues to raise many questions and stimulate interest and curiosity amongst the scientific community. The study of comets is of great interest for understanding the origin of the Solar System and possibly even the origin of Life on Earth and on other solar planets. If the conclusion is drawn that comets were responsible for providing the raw material for Life on our planet, then it may have happened elsewhere in the Universe. Such ideas would strengthen the theory of Panspermia.

It should be noted that astronautical investigations are extremely complex in terms of planning, because everything has to be foreseen in great advance, or otherwise the task may fail; the equipment that a spacecraft can carry depends on an immense variety of factors ranging from weight to cost and applicability. Fortunately, digital microelectronics has developed so much and so quickly that modern equipment tends to become much smaller and more adapted to the performance required of it — not forgetting the high level of automation required to enable operation of spacecraft and their scientific equipment. The costs involved in space missions are linked not only with data collection, but also with the complex treatment of such data, treatment that may take several years and involve numerous multi-disciplinary teams of engineers and scientists. Thus, findings are not always immediate and they do not have the same impact on the media that would be achieved from immediate new findings. The impact of the latter could lead to greater visibility of projects and increasing interest of governments or of private investors. Unfortunately, funds are extremely important for research and scientific progress; if one takes into account all the space missions already completed, the volume of investment is literally astronomical.

15.3 The primitive Life

When in Chapter 8 the "citrate cycle" was mentioned, it implied the involvement of certain species of microorganisms in different steps of the process that perform certain functions or make use of what is produced in them so that the cycle closes. But chemical species are also implied, which from transformation to transformation, also help to close the circle. Wächtershäuser's hypothesis, further developed by Russell and Hall, offers nothing more than an organizational system of the simplest inorganic chemical compounds, as a starting point for materials and metabolisms that we now know are essential for the life of the super-evolved. The *Archaea* are among the most primitive beings that are known, but they have existed on Earth for more than 3.5 Gyr, more than enough for their species to have developed, established and evolved since when they emerged for the first time. From the chemical and functional standpoint, a "simple" cell of a living being, the most primitive that one may imagine, is tremendously complex; in it many different components and chemical compounds interact harmoniously in such an elaborate way that its survival and that of its species is ensured even when agressively tested. Although not generally accepted by the scientific community, the concept that cells of living organisms are symbiotic associations sheds new light on the understanding of the nature of Life, particularly early Life. In an ecological system each component performs a specific function within the community, thus contributing to the survival of all. One is seeing an auto-organization process guided only by an innate tendency to maintain survival, one which develops and refines according to the law of highest energetic yield, a process possibly led by another law, that of natural selection, which is concerned with the adaptation of the system itself. Recent major progress in Genomics, promises that soon the entire genome of dozens of creatures will be known, which should eventually yield important information about their kinship and evolution, a forward step in the knowledge of Life.

The "Cosmic Clock" shows that the differentiation of multicellular organisms from the common algae and trilobites to man, would not have needed more than 0.6 Gyr. However, no less than 3 Gyr were needed for creatures endowed with a cellular and functional differentiation to have arisen. What has happened, in evolutionary terms, for so long? Essentially, the evolution of cellular metabolism in single-celled organisms or in cells of undifferentiated colonies has taken place. Probably by exploring what has happened during the initial 0.7 Gyr one will reach the answer to the many issues that still exist; everything seems to indicate that for such an aim to succeed it will be essential to develop equipment that can probe the Universe at greater and greater distances in space… and time — with telescopes much more powerful than, for example, the Hubble Space Telescope; let us hope that the Atacama complex of radio telescopes, already at a very advanced stage of construction will aid the search. It is very interesting that today in many scientific circles it is thought that most probably the key to the origin and evolution of that primordial phenomenon called Life

Fig. 153
"Falling star", oil on canvas (1884) by Witold Pruszkowski (1846–1896).
National Museum, Warsaw, Poland.
URL: http://commons.wikimedia.org/wiki/File:Witold_Pruszkowski-Spadajaca_gwiazda.jpg

will not be found here on Earth. One can undoubtedly expect that new discoveries will be made as new technologies are developed — for example, what contributions may we expect from the emerging fields of nanotechnology and of micro-instrumentation? Yes, we have to wait expectantly until new answers are found, in order to learn more about our origins, and perhaps — why not? — also find an answer to the disturbing question: Are we alone?

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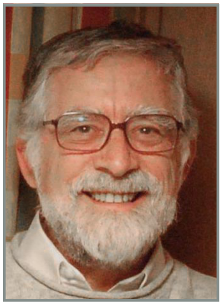
Author index

Subject index

The authors



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